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BROAD SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM PHASE I

FINAL REPORT

by

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GENERAL ELECTRIC COMPANY

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16. Abstract

The Broad-Specification Fuels Combustion Technology Program consists of design and development efforts to evolve promising aircraft gas turbine combustor configurations for burning broadended-properties fuels. Phase I of this program consisted of design and experimental evaluations of three different combustor concepts in sector combustor rig tests. The combustor concepts were a state-of-the-art single-annular combustor, a staged double-annular combustor, and a short single-annluar combustor with variable geometry to control primary zone stoichiometry.

A total of 25 different configurations of the three combustor concepts were evaluated. Testing was conducted over the full range of CF6-80A engine combustor inlet conditions, using four fuels containing between 12% and 14% hydrogen by weight.

Good progress was made toward meeting specific program emisssions and performance goals with each of the three combustor concepts. The effects of reduced fuel hydrogen content, including increased flame radiation, liner metal temperature, smoke, and NO_x emissions were documented. The most significant effect on the baseline combustor was a projected 33% life reduction, for a reduction from 14% to 13% fuel hydrogen content, due to increased liner temperatures.

The use of thermal barrier coatings on the combustor liners, and the use of fuel and air injection features to provide leaner and more uniform primary zone mixtures were shown to offset the effect of reduced fuel hydrogen content.

The single-annular and variable-geometry combustor concepts were selected for further evaluation in Phase II of the program.

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FOREWORD

The program described herein was conducted by the General Electric Company Aircraft Engine Business Group under NASA Contract NAS3-22063. Mr. James S. Fear of the Aerothermodynamics and Fuels Division, NASA-Lewis Research Center, was the NASA Project Manager.

Key General Electric Company contributors were W.J. Dodds, Principal Investigator; E.E. Ekstedt, Technical Program Manager; E.J. Rogala, Program Manager; J.R. Taylor, Combustor Aerodynamics Design; E.C. Vickers, Combustor Mechanical Design; H.L. Foltz, Combustor Heat Transfer; B.T. Keith, Test Hardware Coordination; and J.A. Jasper, Combustor Testing.

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1.0 SUMMARY

The multiphase Broad-Specification Fuels Combustion Technology Program is being undertaken to generate and demonstrate the technology required to utilize broadened-properties fuels in current and next-generation commercial conventional takeoff and landing (CTOL) aircraft engines.

Phase I of the program consisted of design and development efforts to evolve promising combustor configurations with capabilities for accommodating broadened-properties fuels, while meeting several specific emissions and performance goals and generally meeting the combustion system durability requirements of modern turbofan engines. Three basic combustor design concepts were evaluated. These concepts covered a range from those having limited complexity and relatively low technical risk to those having high potential for achieving all of the programs goals at the cost of increased technical risk.

The least complex concept was a single-annular combustor designed for the General Electric CF6-80A engine combustor flowpath. This state-of-the-art combustor is a relatively short design which incorporates the latest developments in fuel injector, dome swirler, and liner film cooling. The second concept was a parallel-staged double-annular design similar to that used in the NASA/GE Experimental Clean Combustor (ECCP) and Energy Efficient Engine (E^3) programs. At light off and low power operating conditions, all of the fuel is burned in a pilot stage, which is designed to provide low velocity, near-stoichiometric primary combustion. At high power conditions, both the pilot and main stages are fueled, but most of the fuel is injected into the main stage. This stage is designed to provide lean combustion and short residence times to reduce NO_x and smoke formation, thereby reducing flame luminosity effects. The third concept was an advanced, short single-annular combustor which employs variable-geometry swirlers to provide optimum flow rates and stoichiometrics in the dome region at the various operating conditions. At light off and low power conditions, the swirlers are closed down to reduce the combustor velocity and to provide near-stoichiometric primary zone mixtures. At high power conditions, the swirlers are opened to provide lean, high

and low power conditions, the swirlers are closed down to reduce the combustor velocity and to provide near-stoichiometric primary zone mixtures. At high power conditions, the swirlers are opened to provide lean, high velocity combustion. The combustion systems based on these concepts were sized for the CF6-80A engine combustor envelope and designed to operate at CF6-80A engine operating conditions, while using broadened-properties fuels.

A total of 25 different configurations of the three combustor concepts were experimentally evaluated in a full scale CF6-80A sector combustor test facility. This facility enabled the 60° sector test combustors to be operated at the full sea-level-takeoff pressure and temperature conditions of the CF6-80A engine. Combustor liner temperatures, flame radiation, pressure drop, exit temperature profiles, and detailed emissions data were obtained in these evaluations.

During the Phase I program, good progress was made toward meeting the program goals with all three of the combustor concepts. The effects of reduced fuel hydrogen content, including increased flame radiation, liner temperatures, and smoke and NO_x emissions were documented; sensi- tivity to changes in fuel hydrogen content was observed to be lower at high power levels than at low power levels; and modifications to reduce the sensitivity of liner temperatures to changes in fuel hydrogen content were demonstrated in all of the combustor concepts. For the baseline single-annular combustor, 33% life reduction was predicted due to increased liner temperatures for a reduction from 14% to 13% fuel hydrogen content. Predicted life reduction was decreased to about 3% in the final configuration of this concept.

The single-annular and variable-geometry combustor concepts were selected for further evaluation in the Phase II program. The single-annular combustor was selected for its overall simplicity and well-developed emissions and performance characteristics. Relatively simple modifications to this combustor concept were demonstrated to offset the durability

reduction due to the use of reduced hydrogen-content fuels. As indicated above, through the use of liner dilution features for smoke reduction, and thermal barrier coatings on the combustor liners, the estimated life reduction for a decrease from 14% to 13% fuel hydrogen content was reduced to less than 3%. Therefore, it was concluded that the use of the more complex, advanced concepts is not warranted in the CF6-80A engine on the basis of fuel flexibility alone. The only program goal which is apparently beyond the capability of this concept is the stringent EPA-proposed NO_x emissions limit, which is no longer in effect.

Although the advanced concepts require further development, both the double-annular and variable-geometry systems were judged to be capable of meeting all of the program goals. The variable-geometry concept was preferred because it requires fewer of the complex fuel nozzle and dome swirler assemblies; the potential for fouling of unfueled main stage nozzles is eliminated; and the ability to continuously vary the swirler airflow provides additional flexibility for intermediate power operation.

The selected combustor concepts are being further developed in the second program phase, which was initiated in December 1981.

2.0 INTRODUCTION

The availability of high quality petroleum middle distillates for jet engine fuel is expected to diminish toward the end of this century. In fact, a recent review of fuel inspection properties for the 1969 to 1979 time period has shown that the majority of jet fuels are already near specification limits for aromatics, freezing point, or smoke point, and that the proportion of fuels having properties near these specification limits is increasing (Reference 1). A trend toward increasing 10% distillation temperature was also reported. These trends toward heavier, high aromatic, reduced hydrogen content fuels will presumably be aggravated by the addition of coal or oil shale derived syncrudes to current feedstocks. Lower quality crudes can be cracked and hydrogenated to meet present fuel specifications, but this process is expensive and consumes large amounts of energy. An alternative to treating the fuel is to incorporate appropriate aircraft and engine modifications to accept fuels with a broader range of properties.

Several recent programs have been conducted to evaluate the effects of fuel properties on the performance and operating characteristics of current engines (References 2, 3, and 4), and additional programs have been conducted to identify and develop combustor technology to use broadened-properties fuels (References 5 and 6). In general, levels of exhaust pollutant emissions increase and the combustor performance and durability requirements become more difficult to meet as the fuel specifications are relaxed. These programs are the result of the following effects incurred in the use of these fuels:

- Higher aromatics content will tend to cause:
  - Increased engine visible smoke output
  - Increased carbon deposition on fuel nozzles and combustor liners
  - Increased flame luminosity, resulting in increased radiative heat transfer to combustor liners and shorter liner life

- Lower fuel volatility and higher viscosity will tend to cause:
  - More difficult cold start and altitude relight
  - Greater difficulty in achieving satisfactory emissions levels at low power conditions
- Poorer thermal stability will tend to cause:
  - Fuel system deposits
  - Fuel injector plugging.

Of the fuel property effects enumerated above, tests conducted to date indicate that the most important for commercial applications is combustor life reduction due to increased flame radiation and resultant increases in combustor metal temperatures. Life reductions of up to one-third have been predicted for a reduction from 14% fuel hydrogen content to 13%, based on analysis of measured liner temperature data in current combustors (References 2 and 3). Obviously, a life reduction of this magnitude would result in a substantial increase in operating cost. Thus the development of combustion systems capable of providing acceptable performance and emissions when using broadened-properties fuels, with no loss in combustor durability relative to present combustors using current fuels, represents an important goal.

The final definition of future fuel specifications will depend on trade-offs between the cost of fuel processing and the cost of combustor modifications to accommodate lower quality fuels. The Broad-Specification Fuels Combustion Technology Program has been initiated by NASA to define the combustor design modifications required to accommodate broadened-properties fuels, so that the trade-offs between combustor modification and relaxation of fuel specifications can be evaluated. This report describes the results of the first phase of the NASA/General Eelectric portion of this overall program.

3.0 PROGRAM DESCRIPTION

The overall NASA Broad-Specification Fuels Combustion Technology Program, which has been described in Reference 7, is a multiyear, multiphase effort being conducted to evolve and demonstrate the technology required to utilize broadened-properties fuels in current and next generation commercial conventional takeoff and landing aircraft engines. The program plan and specific program goals are described below.

3.1 PROGRAM PLAN

The program is being conducted in two sequential, individually funded phases.

3.1.1 Phase I - Combustor Concept Screening

The NASA/General Electric Phase I program, which was completed in February 1982, consisted of the design and experimental evaluation of several different configurations of each of three different combustor design concepts for burning broadened-properties fuels. The three design concepts covered a wide range from those having limited complexity and relatively low technical risk to those having high potential for achieving all of the program goals at the cost of increased technical risk. A series of high pressure, sector combustor component tests, modifications, and retests was conducted with each concept to evaluate its ability to accommodate broadened-properties fuels while meeting several specific emissions and performance goals and demonstrating satisfactory durability characteristics. The end result of this first phase was the selection of the two most promising combustor configurations for further evaluation.

3.1.2 Phase II - Combustor Optimization Testing

The second program phase, which was initiated in December 1981, is a planned 19-month effort to further develop and refine the most promising

combustor configurations identified in the Phase I effort. Phase II tasks will include the redesign of the most promising combustor configuration, based on Phase II results, and an additional series of high pressure sector tests, modifications, and retests to further refine and document the performance, emission, and durability characteristics of these concepts while using several test fuels having a range of properties.

3.2 PROGRAM GOALS

Two different pollutant emission goals, both based on the proposed U.S. Environmental Protection Agency (EPA) standards (Reference 8) as of the start of the Phase I program, are shown in Table 3-1. The proposed standards for engines manufactured after January 1, 1981, with the addition of a NO_x goal, were applied to modifications to the baseline engine combustion system, while standards for engines certified after January 1, 1984, were applied to the more advanced combustion systems.

Program performance goals and specific performance goals applicable to the reference engine are described in Table 3-2. All emissions and performance goals were for operation with an Experimental Referee Broad-Specification (ERBS) fuel defined especially for combustion system research by the 1977 NASA Hydrocarbon Fuels Technology Workshop (Reference 9).

Table 3-1. Design Emissions Goals.

	For Single-Annular Combustor*	For Advanced Combustor Concepts
H	6.7	3.0
CO	36.1	25.0
NO_x	35.3**	33.0
SN	19.2	19.2

HC	Total Unburned Hydrocarbons (g/kN)
CO	Carbon Monoxide (g/kN)
NO_x	Total Oxides of Nitrogen (g/kN)
SN	SAE Smoke Number

* Currently used on CF6-80A Production Engine

** Although no NO_x requirement was specified for engines manufactured prior to January 1, 1984, this goal was included to provide NO_x technology for engines manufactured after that date.

Table 3-2. Design Performance Goals.

- Combustion efficiency, as computed from emissions measurements, greater than 99% at all operating conditions
- Total pressure loss no more than 6% at sea-level takeoff conditions (Design value = 4.7%)

  Combustor-exit-temperature pattern factor (T_4 Max. - T_4 Avg.)/ T_4 Avg. - T_3), no more than 0.25 at sea-level takeoff conditions

T_3	Average measured total temperature at combustor inlet
T_4 Avg.	Average measured total temperature at combustor exit
T_4 Max.	Maximum individual measured total temperature at combustor exit

- Combustor-exit average radial temperature profile factor (T_4 peak - T_4 Avg.)/(T_4 Avg. - T_3), no more than 0.11 at sea-level takeoff conditions

  T_4 peak maximum temperature in average radial profile
- Idle blowout fuel/air ratio no more than 7.5 g/kg
- Altitude relight capability up to 9.14 km
- Carbon-free operation
- No significant resonance within flight envelope

4.0 COMBUSTOR DESIGN APPROACHES

4.1 REFERENCE ENGINE DESCRIPTION

The General Electric CF6-80A engine was selected as the reference engine for all design and experimental studies conducted under the NASA/General Electric Broad Specification Fuels Combustion Technology Program. This engine is an advanced, high pressure ratio turbofan engine that is typical of the large engines that will be developed for commercial airline service within the next 10 years. This reference engine is a short length, lightweight derivative of the very successful General Electric CF6-50 turbofan engine that has been in commercial service for the past 10 years. A layout drawing of the reference engine is presented in Figure 4-1.

Each of the CF6 family engine designs is a high bypass ratio turbofan incorporating a variable stator, high pressure ratio compressor, an annular combustor, an air-cooled core engine turbine, and a coaxial front fan with a low pressure turbine. The CF6-80A engine achieves reduced specific fuel consumption and reduced engine length and weight compared to the basic CF6-50 engine by the use of a high-flow fan with an improved hub design, shorter combustor length, reduced high pressure turbine cooling flow with shroud clearance control, elimination of the turbine midframe, and use of an engine cycle rematch for the new thrust rating.

The CF6-80A engine is especially appropriate as a reference engine for this program because this engine will be in large-scale production in the 1980's and is typical of the modern high pressure ratio engines that will probably be required to use broadened-properties fuels. Intensive development of the CF6-80A engine progressed in parallel with this Phase I program. Therefore, details of the reference engine design were somewhat flexible, particularly prior to certification of the CF6-80A engine in October 1981. Because of this concurrent development of the engine and the broadened-properties fuels combustion systems, it was possible for findings of this NASA program to have an immediate effect on the reference engine design.

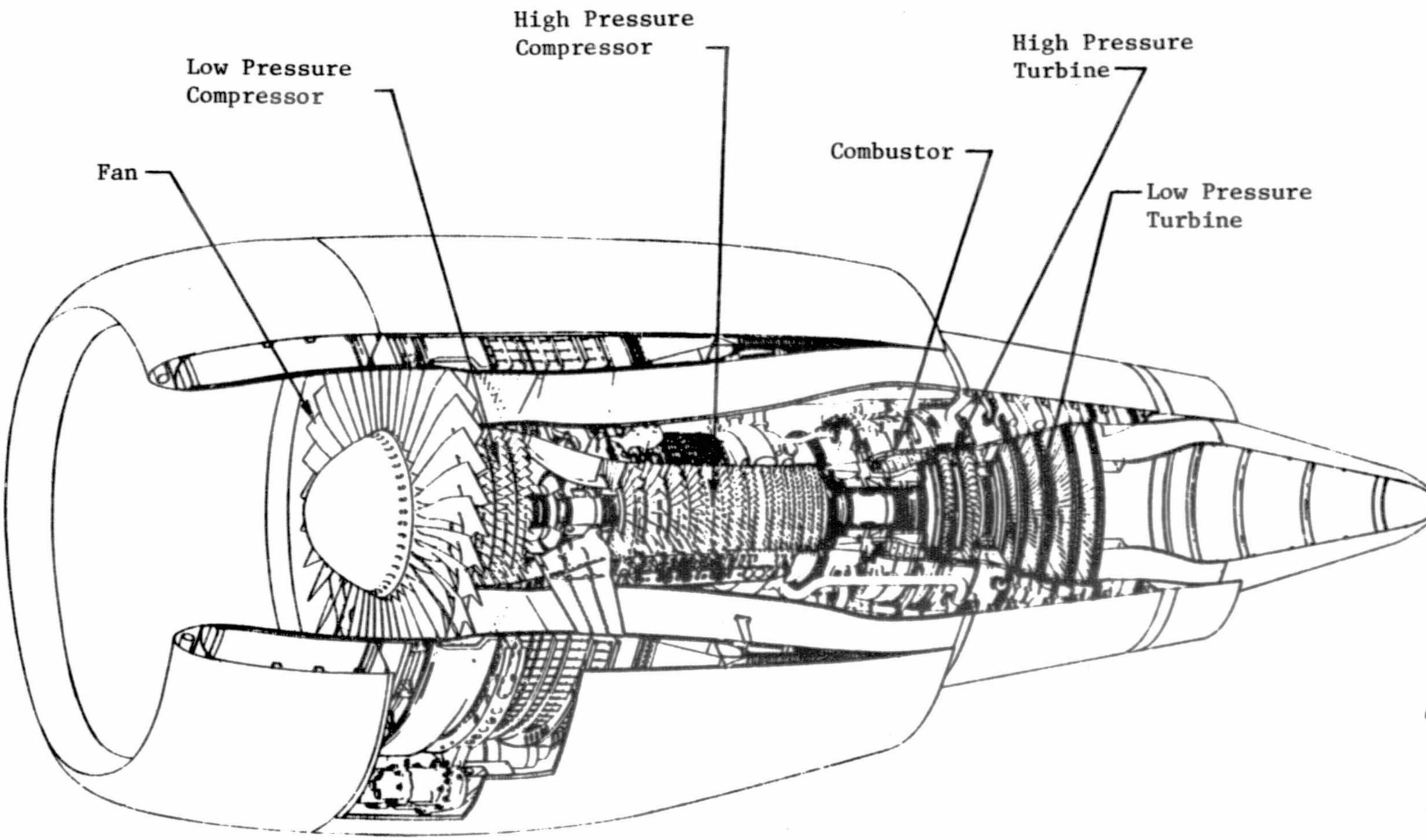

Figure 4-1. General Electric CF6-80A/A1 Turbofan Engine.

The CF6-80A combustor is an advanced-design annular combustor embodying all of the technology improvements evolved during the last 2 decades. Advanced design features include the use of a short, low-pressure-loss step diffuser; a short, compact combustor envelope; rolled ring liner construction with reduced cooling slot overhang length to resist buckling and slot closure; and counterrotating dome swirl cups to provide a uniform fuel/air mixture in the combustor primary zone as a means of reducing smoke and liner hot streaks.

Cycle parameters typical of the CF6-80A combustor at nine engine operating conditions are presented in Table 4-1. Included in this tabulation are (1) the four EPA-specified operating conditions needed for calculating takeoff/landing cycle emissions levels with two possible idle settings; (2) hot day takeoff operating conditions where combustor durability is determined; and (3) cruise operating conditions where the largest portion of the normal flight mission will occur.

The CF6-80A engine combustion system is being developed to meet the CO and HC emissions standards proposed by the EPA for engines with thrust levels greater than 90 kN and scheduled to be certified prior to January 1, 1984. The combustion system design objective is to meet the CO and HC emissions requirements with margins of 20% and 40%, respectively, to allow for measured emissions level variations. The EPA emissions standards applicable to this engine were presented in Table 3-1.

A tabulation of CF6-80A combustor performance goals was presented in Table 3-2. The turbine inlet temperature profile goals for the combustor are presented in Figure 4-2. The guaranteed altitude relight envelope of the engine is presented in Figure 4-3.

All of the combustor concepts described in the following sections were designed to fit within the envelope of the CF6-80A combustor and to operate over the full range of CF6-80A combustor inlet conditions. The CF6-80A performance and operational goals discussed above were applicable to all of the combustor concepts studied in this program.

Table 4-1. Typical CF6-80 Engine Cycle Parameters.

Cycle Condition	Idle	Approach	Climb	Takeoff	Cruise [1]
Net Thrust, kN	8.32	62.50	177.0	208.3	35.6
% Takeoff Thrust	4	30	85	100	---
Combustor Inlet Pressure, MPa	0.301	1.102	2.426	2.789	0.436
Combustor Inlet Temperature, K	431	614	772	805	686
Combustor Reference Velocity, m/s	15.9	20.0	21.6	22.0	20.4
Combustor Fuel/Air Ratio, g/kg	10.7	13.2	21.1	22.8	18.3

(1) Mach No. = 0.80, Altitude = 10.7 km

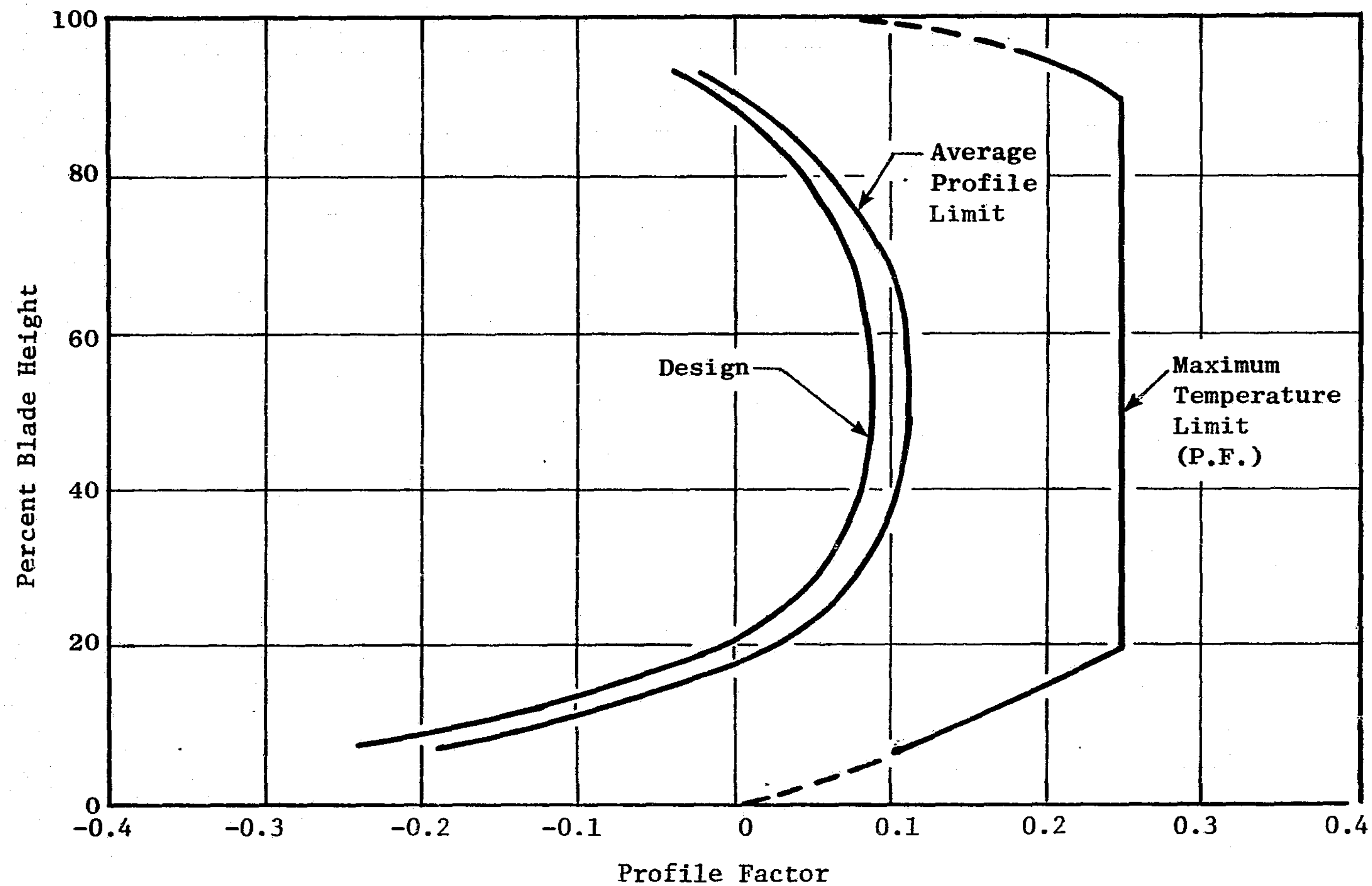

Figure 4-2. CF6-80A Turbine Inlet Temperature Profile Requirement.

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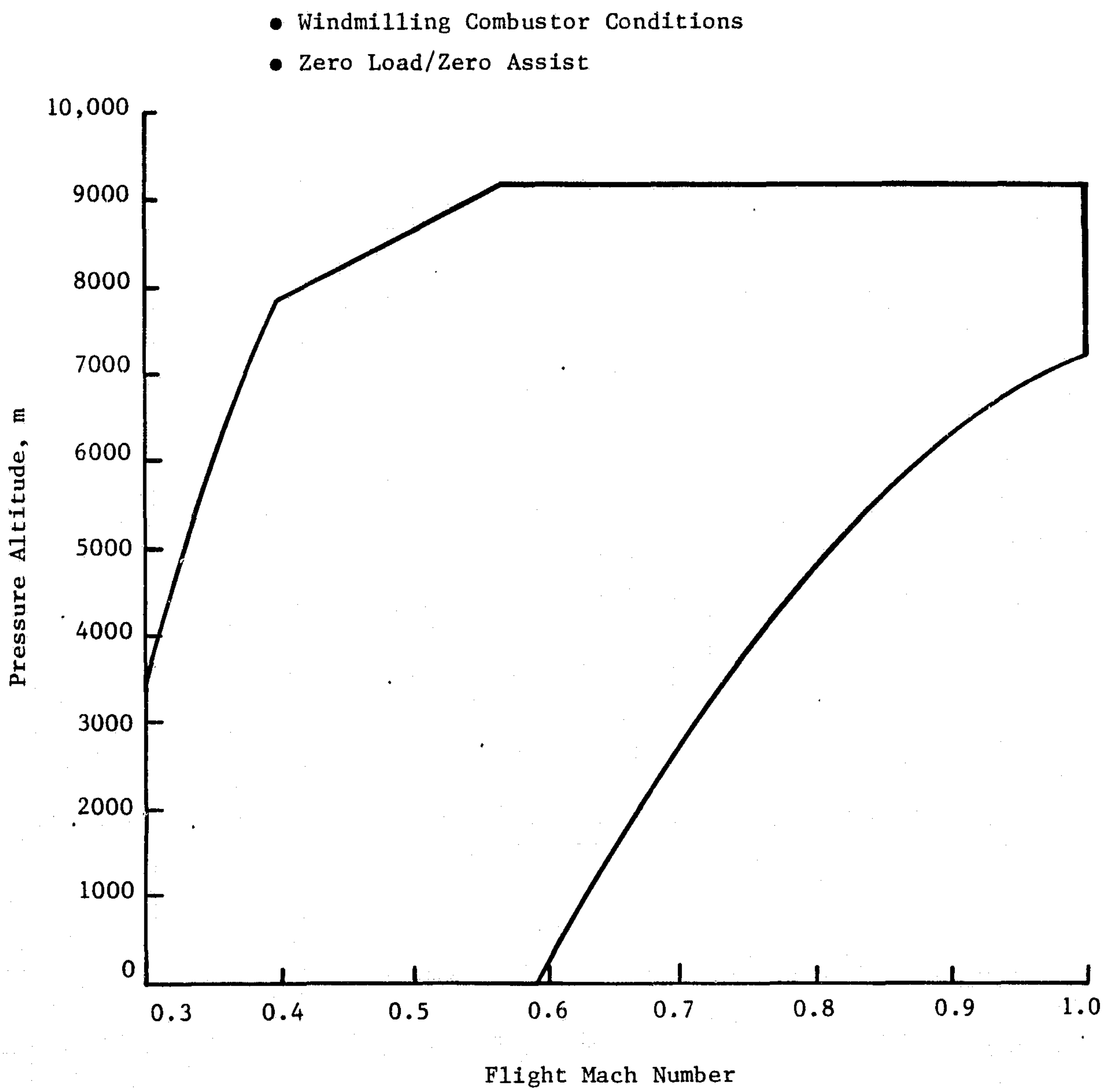

Figure 4-3. CF6-80A Altitude Relight Envelope.

4.2 DESIGN CONSIDERATIONS FOR BURNING BROADENED-PROPERTIES FUELS

The use of broadened-properties fuels in aircraft turbine engine combustion systems presents several combustion system design problems. In general, levels of exhaust pollutant emissions increase and the combustor performance and durability requirements become more difficult to meet as the fuel specifications are relaxed. A breakdown of the key fuel properties and their potential impact on combustor performance, operating characteristics, and durability is presented in Table 4-2. In general, chemical properties (particularly hydrogen content), are important at high power operating conditions, where smoke, flame radiation, carbon deposition, and NO_x all tend to increase as hydrogen content is reduced. Physical properties are more important at low power conditions, where difficulty of ignition and CO and HC emissions tend to increase as viscosity is increased and volatility is reduced.

Of the various effects enumerated in Table 4-2, tests conducted to date indicate that combustor life reduction due to increased flame radiation is by far the most significant. Life analyses reported in Reference 3 predict a 28% life reduction with the F101 combustor when fuel hydrogen content is reduced from 14% to 13%. Predicted life reduction with the J79 combustor is between 11% and 33% (depending on the engine model) for the same 1% reduction in fuel hydrogen content. Life reductions of this magnitude would result in a substantial increase in operating costs. Thus development of combustion systems capable of providing acceptable emissions and performance on broadened-properties fuels, with no loss in combustor durability relative to present combustors burning Jet-A, represents an important goal.

One relatively simple approach to accommodating the higher flame radiation with broadened-properties fuels is to increase combustor cooling. Preferential cooling of the hottest (life-limiting) portions of the combustor, and increased cooling in the forward portion of the combustor, where increased flame radiation is expected to have a comparatively greater effect on the heat load to the combustor walls, could both be employed. Ideally, there would be no loss in liner life when operating with

Table 4-2. Potential Impact of Fuel Properties.

Property Type	Measured Property Trends	Performance Effects	Potential Impact
Chemical	Reduced Hydrogen Content Increased Aromatic Content Reduced Smoke Point Increased Naphthalene Content	Increased Smoke Levels Increased Flame Radiation Increased Carbon Formation/Deposition Increased NO_x Levels	-Increased Exhaust Visibility -Increased Hot Section Metal Temperatures (Decreased Life) -Increased Combustor Hot Streaking/Pattern Factor -Increased Turbine Erosion -Increased NO_x Emissions
Physical	Increased Viscosity Reduced Volatility Increased Density Increased Surface Tension Reduced Vapor Pressure Increased Freezing Point	Increased Fuel Freezing Point Increased Fuel Drop Size Decreased Fuel Evaporation Rate	-Reduced Operational Capability -Decreased Engine Starting Capabilities -Increased CO/HC Levels
Thermal Stability	Reduced JFTOT Breakpoint	Increased Fuel Decomposition/Gumming	-Increased Fuel Injector Plugging -Decreased Fuel Heat Sink

relaxed fuel specifications, and an increase in life could be expected with the use of better fuels; however, increased cooling slot airflow would result in reduced dome and/or dilution flows and a degradation of combustor performance. In particular, combustor exit profiles, pattern factor, and emissions would probably be adversely affected.

An alternative to increased cooling flows is the use of improved liner cooling methods. The use of more efficient film slot designs to increase the film effectiveness would be beneficial in theory, but sizable improvements in film slot design, relative to the current advanced state of development, are unlikely. Thermal barrier coatings applied to the flame side liner surfaces reduce metal temperatures by providing insulation, and can also reduce sensitivity to flame radiation by reflecting a larger portion of the incident radiation than a bare metal surface would reflect. Increased convective cooling on the cool side of the liner can also reduce liner temperatures without increasing cooling flows. Increased cool side convection will tend to reduce both absolute liner temperature and sensitivity to flame radiation, since the hot side convection heat load will generally tend to increase faster than the radiation heat load as cool side convection is increased. Methods to increase cool side convection include the use of convectors to increase local air velocities, or impingement-cooled liners. Use of any of these advanced cooling schemes increases combustor complexity and weight.

Another approach to reduce luminosity effects with broadened-properties fuels is to provide more rapid and thorough fuel/air mixing, which will reduce peak gas temperatures and result in more uniform gas temperature distributions. Improved mixing will also reduce locally rich regions where smoke is formed. By reducing both primary zone smoke levels and peak flame temperatures, flame radiation effects are reduced. Also, improved fuel/air mixing that will result in the elimination of repetitive hot streaks would permit the use of higher average combustor liner heat loads with no increase in liner cooling flow. Fuel/air mixing can be improved by modifying the fuel injectors to obtain improved atomization and a more uniform initial fuel distribution by modifying the air swirl cups

which surround the injectors or by modifying the primary dilution hole patterns for improved mixing with the swirl cup airflow.

In addition to improved mixing, further reductions in flame luminosity effects can be obtained by using lean primary zone burning at high power. This further reduces both primary zone smoke formation and flame temperature. In order to provide lean burning at high power, while still obtaining satisfactory low power emissions and performance, it is necessary to use some type of fuel staging or variable geometry.

Several of the same techniques used to overcome increased liner temperatures with reduced hydrogen fuels can also be used to offset increases in pollutant emissions caused by the use of broadened-properties fuels. These include better fuel atomization, achieved with higher fuel pressures or with improved air-blast dome swirlers, and better swirl cup and dilution flow mixing. Increased dome cooling effectiveness and reduced amounts of dome cooling flows would reduce idle CO and HC emissions levels. The most significant reductions in pollutant emissions can be achieved, however, by employing combustor design concepts that use two-stage combustion or variable geometry to provide rapid, lean burning at high engine power conditions and slow, rich burning at low engine power conditions.

The reduced fuel volatility and increased viscosity of broadened-properties fuels will result in increased fuel/air ratios for engine cold starting and will increase the difficulty of achieving the required altitude relight performance. Techniques to improve cold starting and altitude relight performance include higher fuel pressure and better air-blast swirl cup designs to improve fuel atomization at these conditions. Many other techniques are available to improve light-off performance, including variation and optimization of igniter axial and circumferential location, igniter immersion, igniter energy, fuel spary pattern, and airflow velocity and direction in the vicinity of the igniter tip location.

Thermal stability problems caused by the use of broadened-properties fuels, including increased fuel system deposits and fuel injector

plugging, can be offset by reducing maximum fuel temperature limits or, alternatively, by the use of techniques such as improved thermal insulation; relocation of fuel valves to cooler areas of the engine, away from the combustor; and the use of low pressure fuel nozzle tips having large passages and orifices to avoid plugging. Increased levels of carbon deposition of fuel nozzles and combustor liner surfaces are not expected to be a problem in current design, but care must be taken to ensure that modified swirler and fuel nozzle tip designs provide carbon-free operation.

In general, combustor fuel tolerance is expected to be improved by any technique which provides improved atomization or mixing in the combustor primary zone. One exception is the desirability of a low pressure drop fuel nozzle tip to resist plugging, which can adversely affect fuel atomization. Here, the use of a dual orifice fuel nozzle having a well insulated high pressure primary orifice for good low power atomization and a low pressure air-atomizing secondary design for high power, or improved low pressure fuel nozzle/swirl cup designs could be utilized. Further improvement in fuel tolerance can be obtained by using advanced lean burning designs. The specific combustor concepts and modifications evaluated in this program are described in the following section.

4.3 COMBUSTOR CONCEPTS AND MODIFICATIONS

The three different combustor concepts evaluated in this program were an advanced single-annular combustor representative of those used in recently developed engines; a double-annular combustor concept which had previously been demonstrated in several emissions reduction oriented programs (References 10, 11, and 12); and a new ultra-short signle-annular combustor with variable geometry, which had not previously been demonstrated. A baseline configuration and at least five modifications of each concept, as described below, were experimentally evaluated.

4.3.1 Single-Annular Combustor

The least complex of the systems evaluated in this Phase I program was the basic single-annular combustor. A cross-sectional view of the

single-annular combustor sized for the CF6-80A engine is shown in Figure 4-4. A photograph of a sector of this combustor is shown in Figure 4-5. This combustion system is an advanced derivative of the CF6-50 design which has been described in detail in Reference 9. The CF6-80A combustor dome structure is identical to the CF6-50 design, having provisions for mounting 30 swirl cups, one for each fuel nozzle.

One advanced design feature of the CF6-80A is the use of advanced counterrotating swirl cups, each of which contains a clockwise rotating primary swirler and a counterclockwise rotating secondary swirler, both mounted concentrically with the fuel nozzle tip. The primary swirler is constrained axially, but is able to "float" radially relative to the secondary swirler to allow for differential thermal growth and distortion between the combustor and engine casing. The radial position of this primary swirler is then determined by the fuel nozzle tip. This counterrotating swirl cup design, which replaced the simple axial swirler used in the CF6-50 combustor, provides improved fuel atomization and primary zone mixing.

Other advanced design features incorporated in the CF6-80A combustor include a 3-inch combustor length reduction relative to the CF6-50, a 6-inch length reduction in the low pressure-loss step diffuser, and the use of a newly developed film cooling slot design that features improved film cooling effectiveness and maximum resistance to thermal distortion, which can cause the film cooling slot to close. As shown in Figure 4-4, the CF6-80A combustor is mounted to the engine casing at the aft end of the liners to reduce aft seal leakage.

The CF6-80A obtains low CO and HC emissions at idle by utilizing fuel staging, wherein several of the fuel nozzles are shut off at low power. In early development, a 4/2 staging configuration with four nozzles fueled, two shut off, four more fueled, etc., was used. Later, in the certification engine, a 5/1 staging configuration was used.

CO and HC have also been reduced with the development of improved fuel nozzle tips having a pressure atomizing primary orifice and a low pressure secondary. A fuel pressure controlled valve shuts off to the

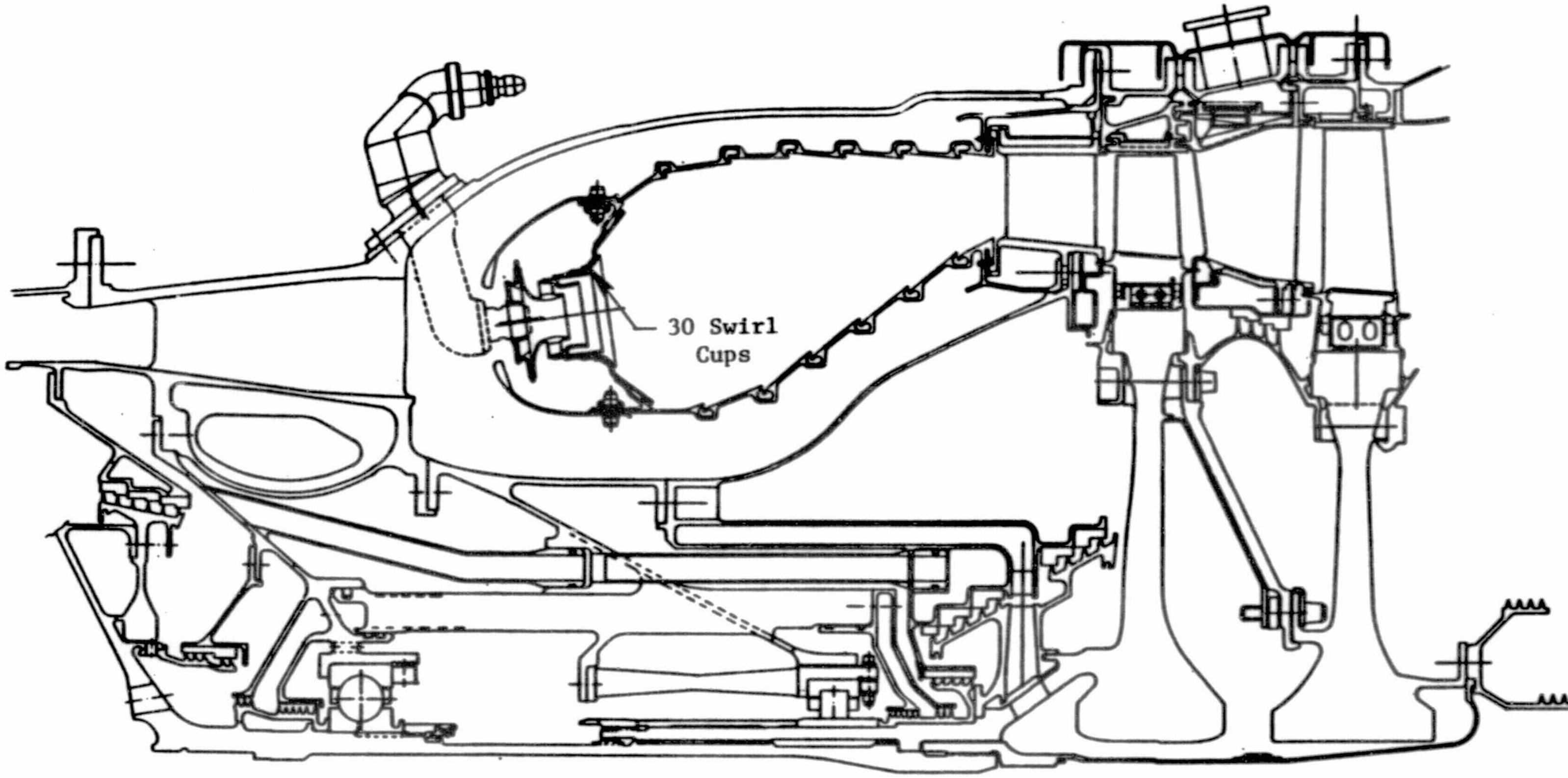

Figure 4-4. Single-Annular Combustor.

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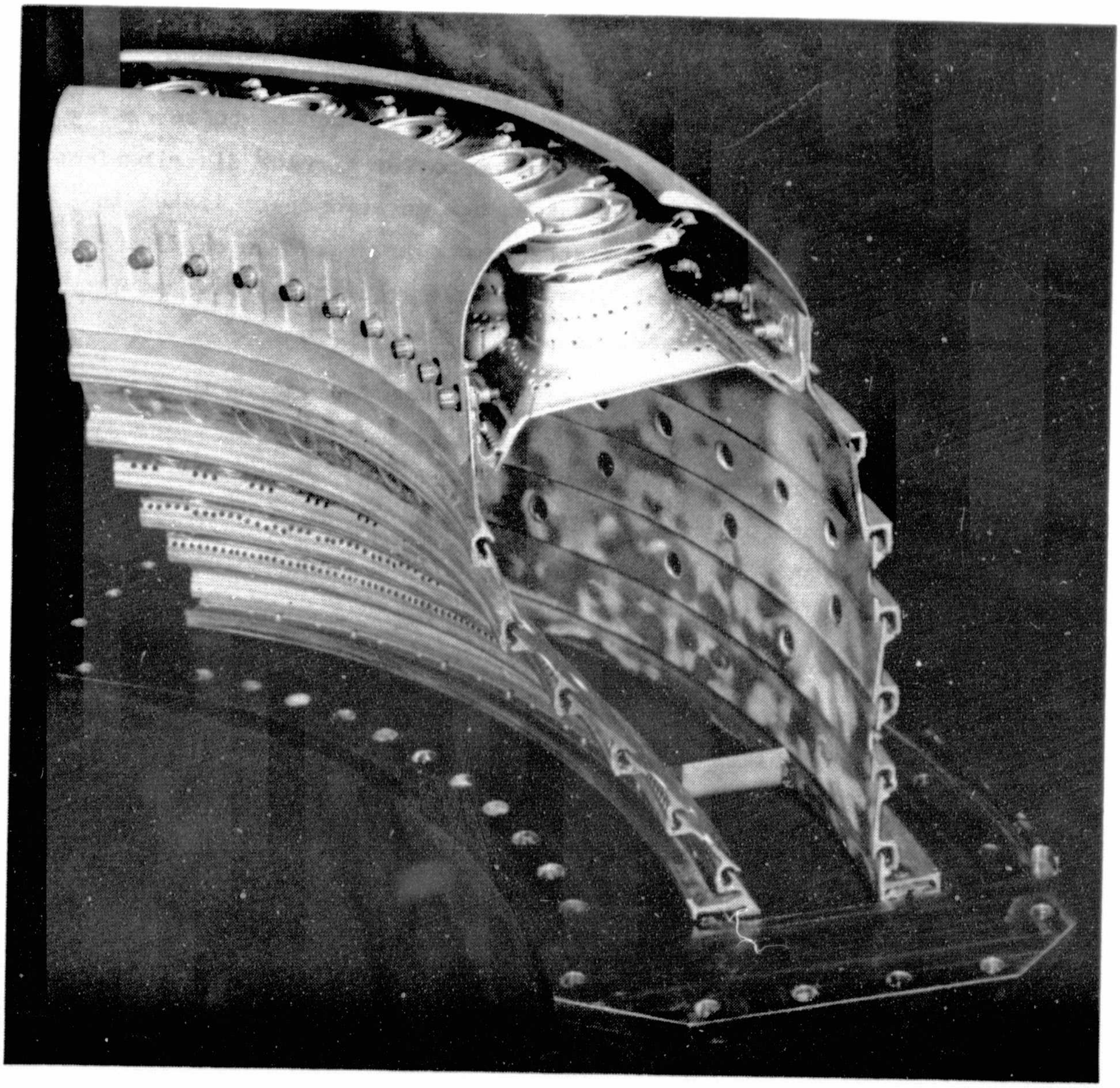

Figure 4-5. Single-Annular Sector Test Combustor.

secondary orifice at low power conditions. For fuel staging, the primary orifice is blocked to eliminate fuel flow at low power. The CF6-80 fuel nozzles incorporate an improved insulation design in the fuel nozzle stem and an outboard-mounted fuel valve to resist fuel coking and fouling.

A total of 10 single-annular combustor configurations were evaluated. The combustor modifications incorporated in each of these configurations are summarized in Table 4-3. The combustor airflow distributions for each of the single-annular combustor configurations are listed in Table 4-4. All of these airflow distributions are based on airflow calibration results with actual test hardware. The original design airflow splits are also shown for comparison.

The first seven single-annular combustor configurations were primarily concerned with identifying a promising combination of liner dilution pattern and fuel nozzle shroud flow and fuel flow schedules to provide a leaner, more uniform primary zone fuel/air mixture for low smoke and good fuel tolerance at high power, while still maintaining good low power emissions and performance.

The liner dilution thimbles used to improve primary dilution jet penetration in Configurations S-5 and S-6 are shown in Figure 4-6. Except for the dilution thimbles, all dilution holes were basically circular punched holes. The edges of these holes were slightly beveled at the inlet, but no special hole contours were used to try to influence dilution jet penetration strength or angle. The flow through the dilution thimble was estimated to be about 50% higher than the flow through a flat dilution hole of the same size due to the improved discharge coefficient of the thimble. Three different types of fuel nozzles were used, as shown in Figures 4-7 and 4-8. All of these nozzles used shrouded dual-orifice, pressure atomizing tips as shown in the inset.

The CF6-80A baseline tip was used in all but three of the tests. However, for Configuration S-2, the primary-to-secondary orifice fuel flow schedule was changed to evaluate fuel injection effects. For that configuration, primary orifice flow was increased from the nominal 16% up to 33% of total fuel flow at the takeoff operating condition and from 20% to

Table 4-3. Single-Annular Combustor Modifications.

Modification	Intent	Configuration[a]									
		S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10
Baseline swirler		Ⓧ	X	X	X	X	X	X		X	X
Baseline dilution		Ⓧ	X								
Baseline fuel nozzle		Ⓧ		X			X	X	X	X	X
Increased primary fuel nozzle orifice flow at high power	Improved atomization/reduced spray angle		Ⓧ								
Increased primary dilution (inner liner only)	Improved primary zone mixing leaner primary zone			Ⓧ	X						
Increased fuel nozzle shroud flow	Improved atomization leaner primary zone				Ⓧ	X					
Increased primary dilution with dilution thimbles	Improved primary zone mixing leaner primary zone					Ⓧ	X				
Increased primary dilution without dilution thimbles	Improved primary zone mixing leaner primary zone							Ⓧ	X	X	X
Advanced swirler configuration	Improved primary zone mixing								Ⓧ		
Flattened dome contour	Improved primary zone mixing								Ⓧ	X	X
Thermal barrier coatings	Reduced liner temperatures									Ⓧ	X
Improved primary swirler retainer	Combustor durability										Ⓧ

(a) Ⓧ = Primary modification(s) under evaluation in specified configuration.

X = Modifications retained from previous configurations.

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Table 4-4. Single-Annular Combustor Airflow Distributions.

Location	Percent of Total Combustor Airflow									Baseline Design
	S-1/S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	
Swirl Cups										
Nozzle Shroud	0.80	0.78	1.17	1.79	0.78	0.80	0.80	0.80	0.80	0.80
Swirlers	19.79	19.28	19.21	18.78	18.97	19.68	19.68	19.68	19.68	19.41
Total[a]	20.59	20.06	20.38	20.57	19.75	20.48	20.48	20.48	20.48	20.21
Dilution										
Outer Liner, Primary[a,b]	-	-	-	3.63	3.67	2.44	2.44	2.44	2.44	-
Secondary[b]	11.80	11.51	11.47	10.89	11.00	11.37	11.37	11.37	11.37	13.16
Inner Liner, Primary[a,b]	-	2.54	2.53	3.88	3.92	2.48	2.48	2.48	2.48	-
Secondary[b]	19.01	18.52	18.45	13.82	13.95	14.87	14.87	14.87	14.87	20.88
Total	30.81	32.57	32.45	32.22	32.54	31.16	31.16	31.16	31.16	34.04
Cooling										
Outer Liner	12.82	12.49	12.44	12.58	12.71	12.75	12.75	12.75	12.75	12.14
Dome[a]	18.11	17.65	17.58	17.25	17.45	18.02	18.02	18.02	18.02	17.23
Inner Liner	16.95	16.52	16.46	16.79	16.96	16.86	16.86	16.86	16.86	15.65
Seal Leakage	0.73	0.71	0.71	0.59	0.61	0.73	0.73	0.73	0.73	0.73
Total	48.61	47.37	47.19	47.21	47.71	48.36	48.36	48.36	48.36	45.75
Primary Zone	38.70	40.25	40.49	45.33	44.77	43.42	43.42	43.42	43.42	37.44
Combustor Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

a) Included in Primary Zone Airflow
b) Liner Primary = Panels 0 and 1, Secondary = Panels 2-5

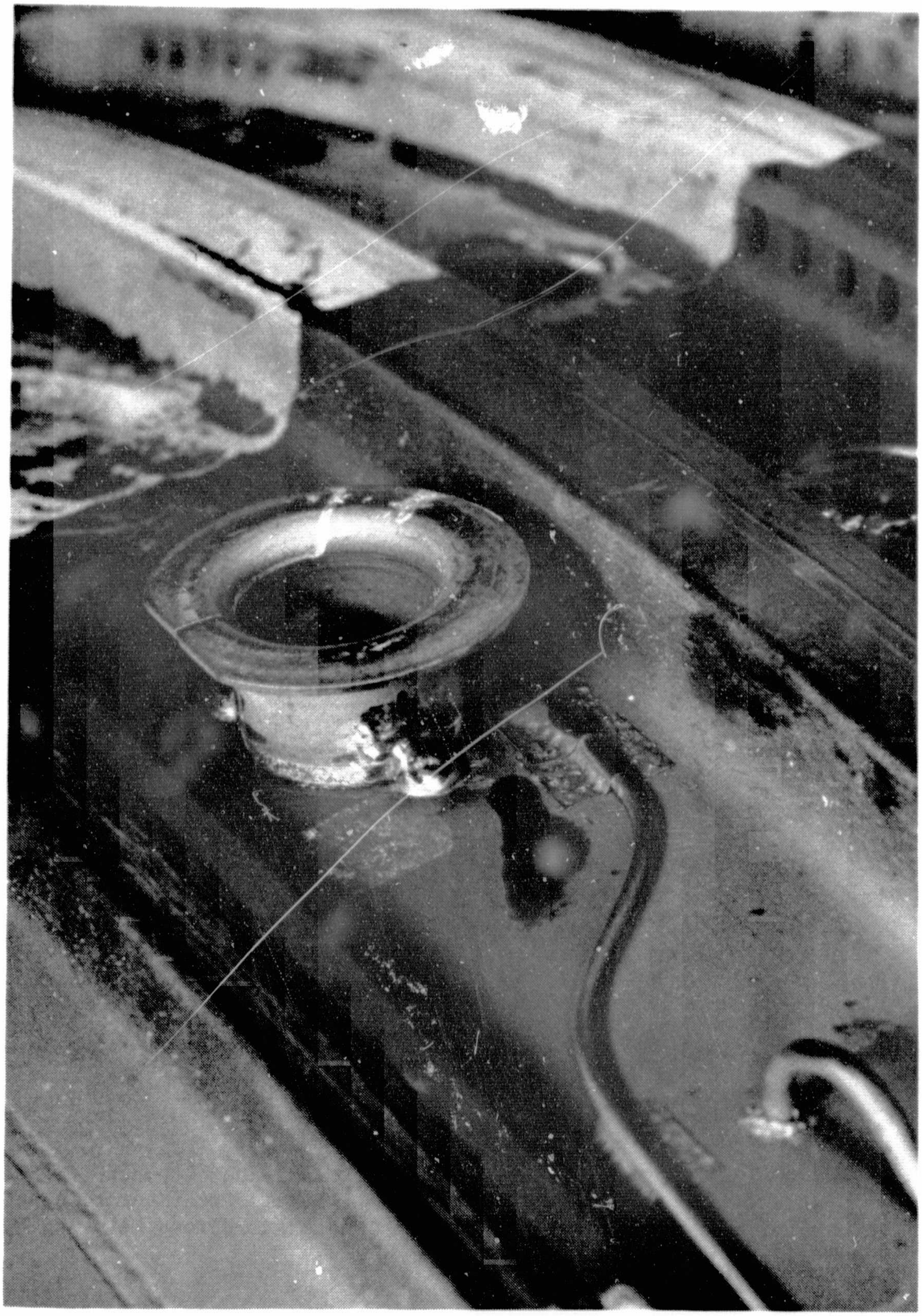
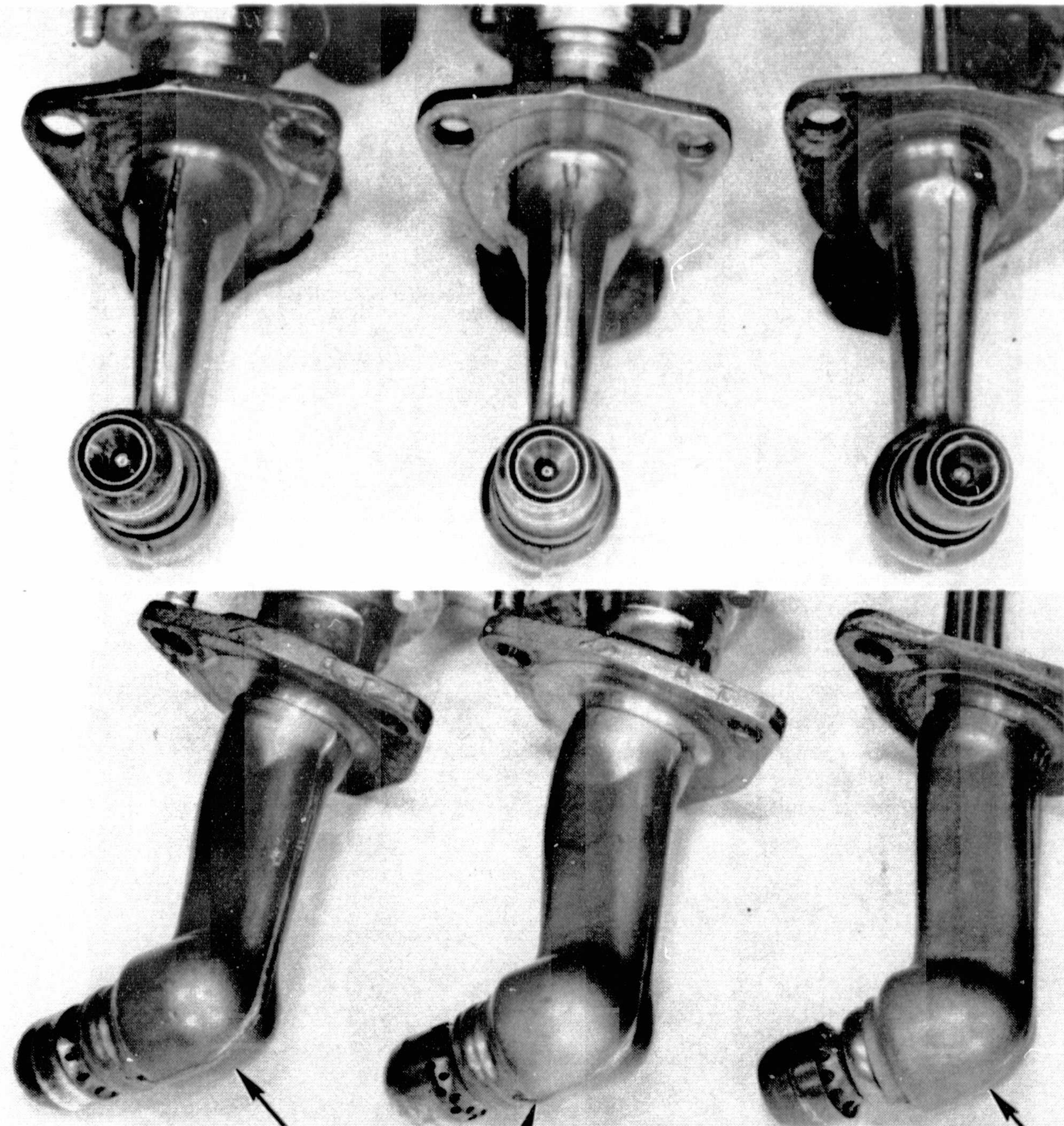


Figure 4-6. Liner Dilution Thimble.



(A) CF6-80A Baseline

(B) CF6-80A Baseline with Increased Shroud Flow (Configuration S-4) Double Row of Shroud Metering Holes

(C) Early Development CF6-80A Nozzle (Configuration S-5) Larger Shroud Metering Holes

Figure 4-7. Single-Annular Fuel Nozzle Tips.

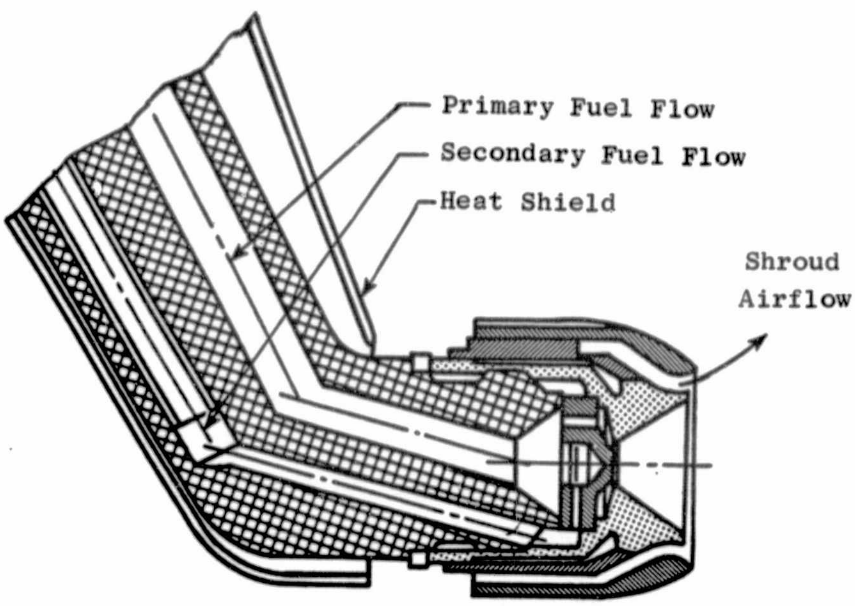


Figure 4-8. Fuel Nozzle Tip Detail.

48% at climb. This had the effect of narrowing the effective spray angle slightly and improving the atomization by increasing both primary orifice pressure drop and secondary orifice atomizing air-to-fuel ratio. Shroud flow was increased in Configuration S-4 to increase atomizing airflow for the secondary fuel. Shroud flow is critical for secondary fuel atomization since pressure drop across the secondary orifice is very low (less than about 0.2 MPa). Shroud flow was further increased by using an earlier type of CF6 fuel nozzle tip in Configuration S-5.

Configuration S-8 incorporated substantial modifications to the combustor dome with the incorporation of the advanced air-blast/radial swirler shown in Figures 4-9 and 4-10 and a slightly flattened dome contour. The intent of these modifications was to improve circumferential spreading and mixing by increasing the fuel spray angle. Configuration S-9 incorporated the best fuel nozzle, swirler, dome, and liner dilution features of the previous eight configurations, in addition to the use of ceramic thermal barrier coatings for reduced liner temperatures. The thermal barrier coating was a 0.25 mm thickness of yttria stabilized zirconia on a 0.13 mm NiCrAlY bond coat. Configuration S-10 was identical to S-9 except for a mechanical design improvement to eliminate cracking of the primary swirler retainer, which was a problem with S-9.

Test results obtained with these single-annular combustor configurations are discussed in Section 4.1.

4.3.2 Double-Annular Combustor

The parallel staged, low emissions double-annular combustor concept originally developed for the NASA/General Electric Experimental Clean Combustor Program was selected as the second design concept for the Phase I program. This design concept, scaled to fit within the CF6-80A combustor casing, is illustrated in Figure 4-11. A photograph of the sector combustor evaluated in the Phase I program is presented in Figure 4-12.

The double-annular combustor incorporates two concentric annular domes separated by an annular centerbody. At light off and low engine power operating conditions, all of the fuel is injected into the outer

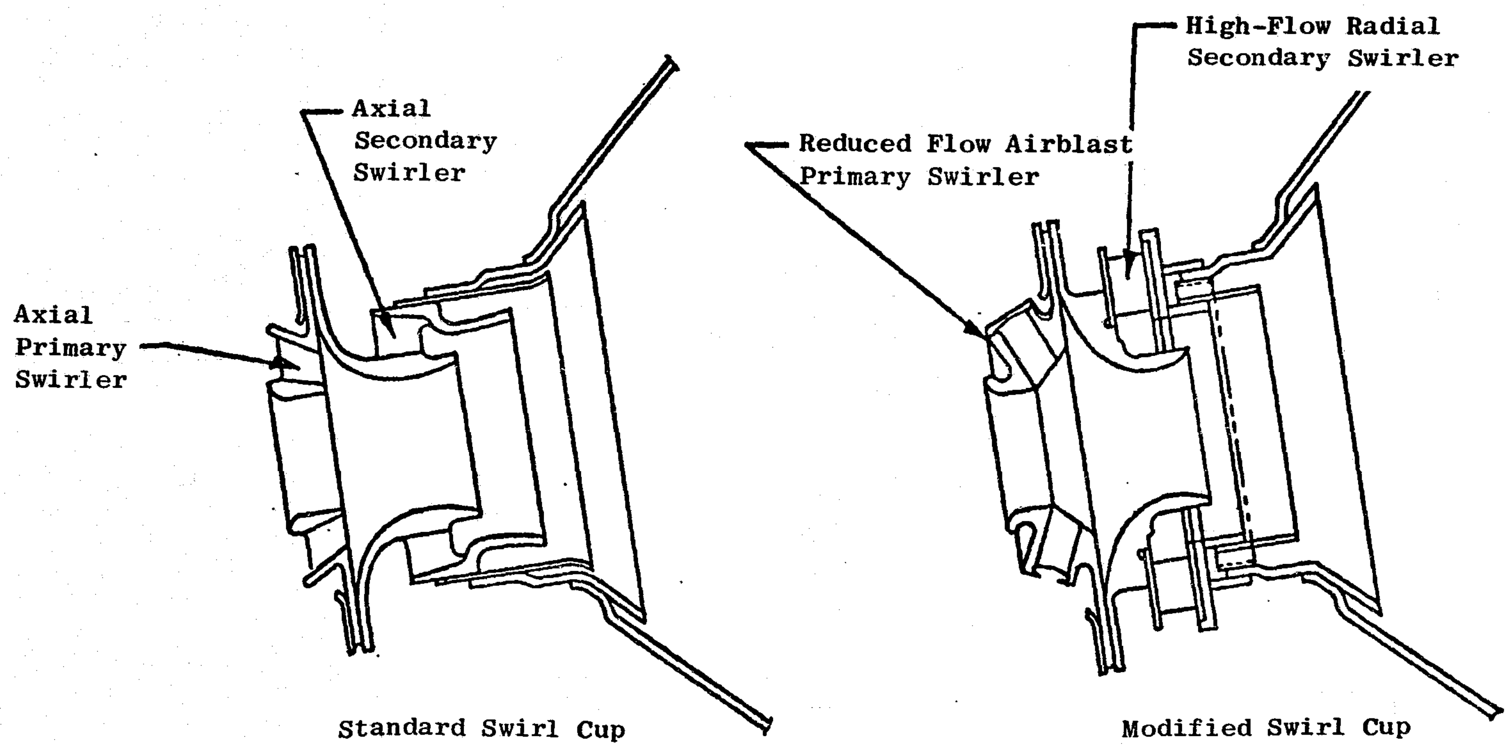


Figure 4-9. Modified Swirl Cup Used on Configuration S-8.

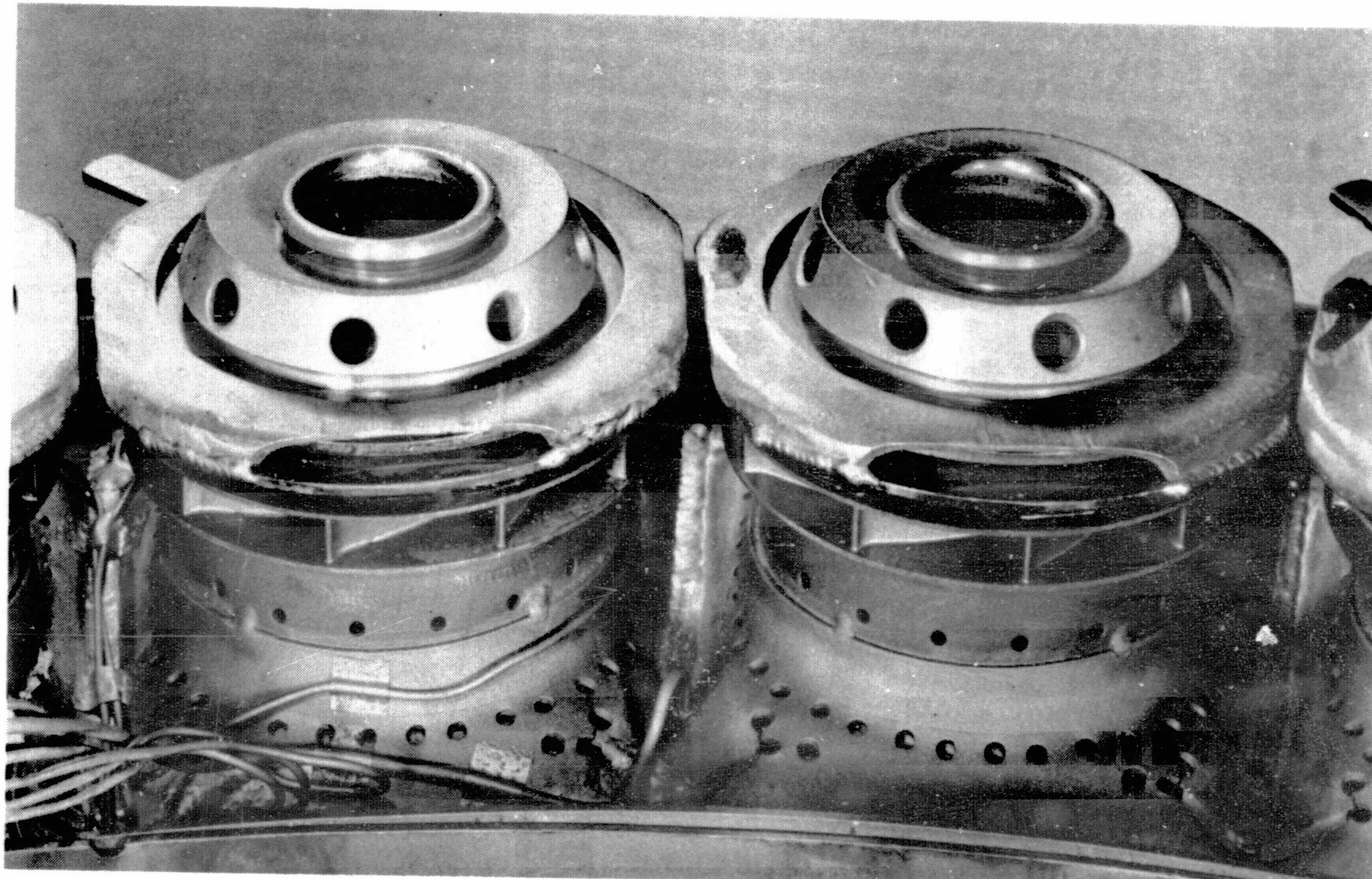


Figure 4-10. Photograph of Advanced Swirler for Single-Annular Combustor.

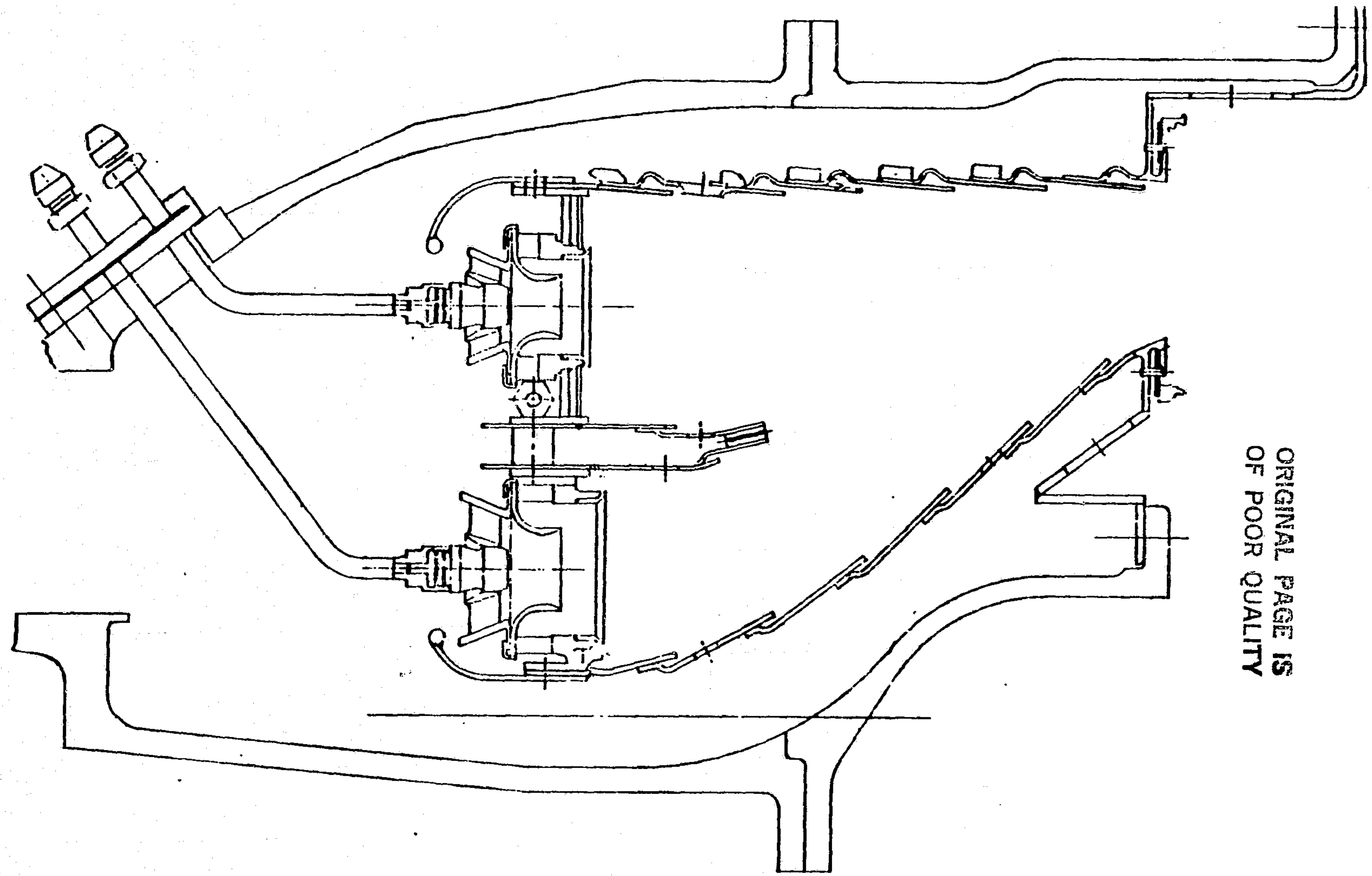


Figure 4-11. Double-Annular Combustor.

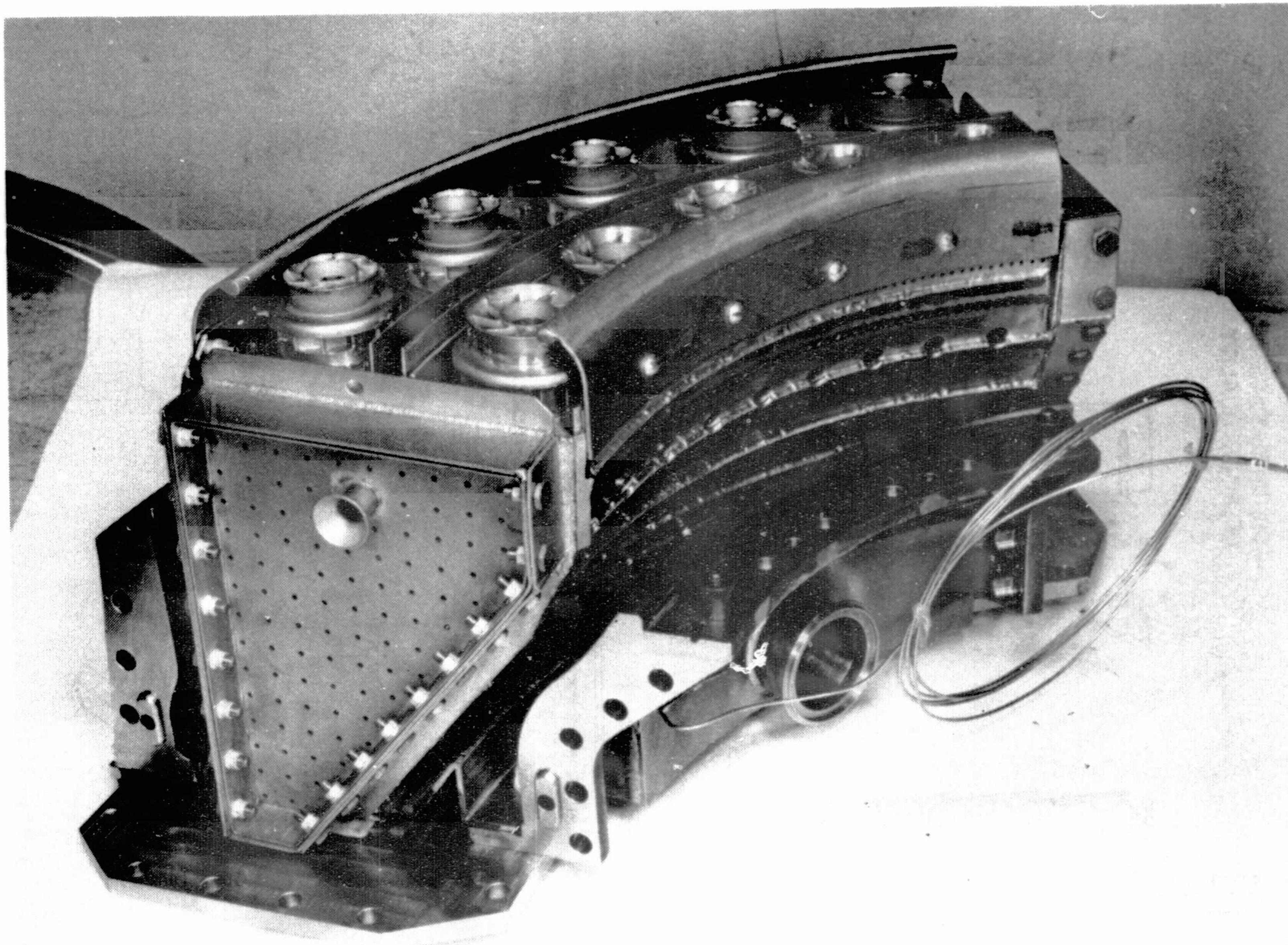


Figure 4-12. Phase I Program Double-Annular Sector-Combustor.

annulus dome (pilot stage). The outer dome swirlers admit only about 14% of the total combustor airflow. In this manner, near-stoichiometric fuel/air ratios are maintained in the low velocity and long residence time outer dome region, resulting in high combustion efficiency and low CO and HC emissions at these low power conditions. The inner annulus dome (main stage) and primary dilution holes admit about 45% of the total airflow. At high power engine operating conditions, increasing percentages of fuel flow are supplied to the inner annulus dome, and at full engine power conditions, about 70% of the total fuel flow is supplied to the inner annulus. Consequently, lean combustion is maintained in both annuli, and very short residence times exist in the high velocity inner annulus dome. As a result of the lean combustion and short residence times, low NO_x and smoke levels are produced. Flame radiation is also reduced due to lower flame temperatures and smoke level, thereby decreasing sensitivity of combustor liner temperatures to fuel hydrogen content.

Design parameters of the CF6-80A double-annular combustor evaluated in the Phase I program are compared to those of double-annular combustors designed for the NASA/General Electric Experimental Clean Combustor (Reference 10) and Energy Efficient Engine (Reference 12) Programs in Table 4-5. All of the design values for the CF6-80A combustor are fairly conservative, with a majority falling between the previous designs.

Several of the significant double-annular combustor design features are shown in Figure 4-13. This combustor uses a simplified flat dome design similar to that successfully used in Phase I of the NASA/GE Experimental Clean Combustor Program (Reference 10) and in the NASA/GE Quiet Clean Short Haul Experimental Engine Double-Annular Combustor Program (Reference 11). Both the pilot and main stage domes incorporate counterrotating swirl cups based on components used in the NASA/GE Energy Efficient Engine Program. These advanced swirl cups have axial primary swirlers with radial inflow secondary swirlers. Pressure atomizing simplex fuel nozzles were used in both the pilot and main stages for this program, although a dual orifice pilot stage fuel nozzle would probably be required to obtain satisfactory atomization at light-off conditions in an

Table 4-5. Double-Annular Combustor Design Parameters.

Combustor Design	CF6-50 Double Annular	E^3 Double Annular	CF6-80 Double Annular
Combustor Length, cm	32.8	17.8	22.1
Outer Dome Height, cm	6.9	6.1	7.1
Inner Dome Height, cm	6.1	5.6	5.6
Outer Length/Dome Height	4.8	3.0	3.1
Inner Length/Dome Height	5.4	3.3	4.0
No. of Fuel Injectors	60	60	60
Reference Velocity, m/s	23	17	22
Space Rate, J/s-Pa-m^3	623	715	695
Outer Dome Velocity, m/s	9.8	9.1	9.0
Inner Dome Velocity, m/s	27	17	29
Outer Passage Velocity, m/s	37	41	42
Inner Passage Velocity, m/s	46	37	50

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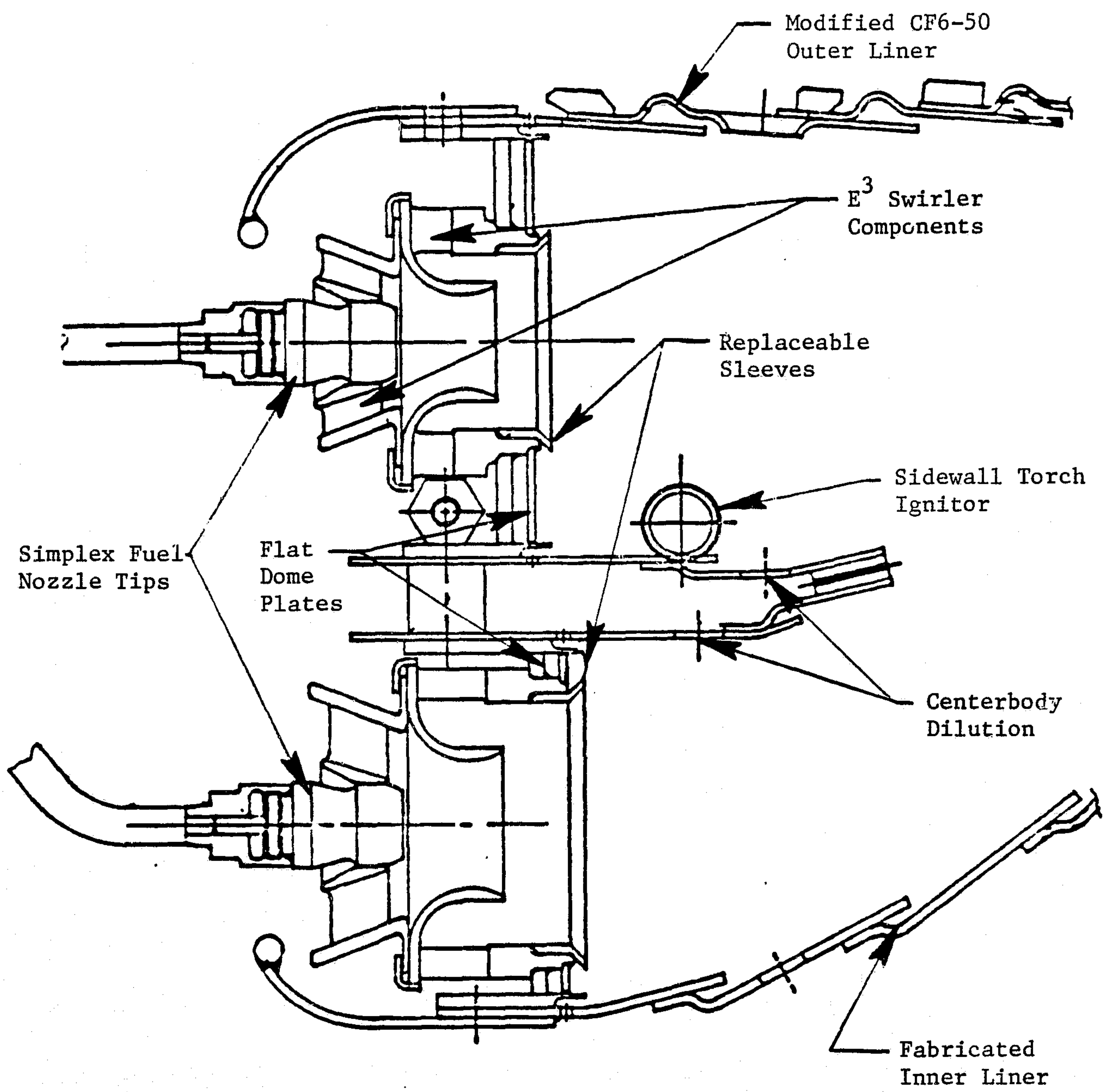

Figure 4-13. Double-Annular Combustor Design Features.

actual engine application. The baseline fuel nozzle tips had an air shroud similar to that used on the CF6-80A combustor to prevent carboning. The centerbody was designed to accommodate dilution holes to improve mixing in both the pilot and main stage dome regions. Combustor liner construction and cooling are conventional, with stacked ring construction and convective backside cooling. As with the flowpath design variables, selection of double-annular design features was fairly conservative.

A total of six double-annular combustor configurations were evaluated during this Phase I program. The combustor modifications incorporated in each of these configurations are summarized in Table 4-6. Airflow distributions based on airflow calibration of the test hardware are presented in Table 4-7.

Several of the modifications to this concept were defined with the objective of reducing CO and HC emissions at idle. Pilot stage dome, liner, and centerbody cooling were reduced in Configuration D-2 to reduce quenching of CO and HC in the cooling film. At the same time, pilot stage (outer liner) dilution was moved aft to increase effective pilot stage residence time. Pilot stage cooling flows were again reduced in Configuration D-5, and thermal barrier coatings were applied to protect the pilot stage dome and liners with this reduced flow. A pilot stage swirler modification was also evaluated for idle emissions reduction. Swirler spray visualization and patternation tests conducted with the baseline pilot stage swirler indicated that the baseline spray pattern was rather narrow, Figure 4-14(a). The alternative short-barrel configuration shown in Figure 4-15, which has a much wider, hollow cone pattern, Figure 4-14(b), was then developed. This short-barrel configuration also prevents wetting of the sleeve and splash plate, which can lead to high HC emissions. This swirler was incorporated into Configuration D-3 and all subsequent double-annular combustor configurations.

The effect of fuel atomization on idle emissions was also evaluated. In the final three double-annular combustor configurations, the standard pilot stage fuel nozzle tip was replaced with the simplified development tip design shown in Figure 4-16. This development tip is a

Table 4-6. Double-Annular Combustor Modifications.

Modifications	Intent	Configuration					
		D-1	D-2	D-3	D-4	D-5	D-6
Baseline		(X)					
Reduced pilot dome cooling	Reduced quenching of CO and HC at idle		(X)	X	X	X	X
Reduced pilot liner/centerbody cooling	Reduced quenching of CO and HC at idle		(X)	X	X		
Pilot liner dilution moved aft	Reduced quenching of CO and HC at idle		(X)	X	X	X	X
Modified swirler on pilot stage	Improved atomization/mixing for reduced CO and HC at idle			(X)	X	X	X
Rich main stage	Improved intermediate power emissions and performance			(X)	X	X	X
High pressure drop development fuel nozzles on pilot stage	Improved pilot stage atomization for reduced CO and HC at idle				(X)	X	
Thermal barrier coatings on dome and liners	Reduced liner temperatures					(X)	X
Low pressure drop development fuel nozzles on pilot stage	Pilot stage atomization evaluation						(X)
Further reduced pilot/centerbody liner cooling	Reduced quenching of CO and HC at idle					(X)	X

Table 4-7. Double-Annular Combustor Flow Distributions.

Location		Flow, Percent of Total Combustor Airflow						
		D1	D2	D3	D4	D5	D6	Design
Outer Swirl Cups								
Nozzle Shroud		1.06	1.05	1.05	----	----	----	1.05
Primary Swirler		3.92	3.89	3.89	3.93	4.06	4.06	4.20
Secondary Swirler		9.40	9.32	9.32	9.42	9.73	9.73	9.02
Total a		14.38	14.26	14.26	13.35	13.79	13.79	14.27
Inner Swirl Cups								
Nozzle Shroud		0.98	0.97	0.97	0.98	1.01	1.01	1.36
Primary Swirler		9.28	9.20	9.20	9.30	9.61	9.61	7.45
Secondary Swirler		23.49	23.30	11.65	11.77	12.16	12.16	24.45
Total b		33.75	33.47	21.82	22.05	22.78	22.78	33.26
Dilution	Panel 0 a	----	----	----	----	----	----	----
Outer Liner	Panel 1 a	4.10	2.03	2.03	2.05	2.12	2.12	3.78
	Panel 2	----	5.21	5.21	5.27	5.44	5.44	----
	Panel 3	2.80	2.78	2.78	2.81	2.90	2.90	2.31
Centerbody	Outer a	2.04	2.02	2.02	2.04	2.11	2.11	1.78
	Inner b	4.77	4.73	4.73	4.78	4.94	4.94	4.41
Inner Liner	Panel 0 b	----	----	----	----	----	----	----
	Panel 1 b	4.48	4.44	4.44	4.49	4.64	4.64	4.30
	Panel 4	2.45	2.43	14.08	14.24	14.71	14.71	2.41
Total b		20.64	23.64	35.29	35.67	36.85	36.85	18.99
Cooling								
Outer Liner		8.95	8.30	8.30	8.39	6.75	6.75	8.29
Outer Dome a		4.13	2.77	2.77	2.80	2.89	2.89	4.62
Centerbody	Outer	2.24	1.77	1.77	1.79	0.46	0.46	2.31
	Inner	3.48	3.45	3.45	3.49	3.61	3.61	3.88
Inner Dome b		2.61	2.59	2.59	2.62	2.71	2.71	3.04
Inner Liner		9.01	8.94	8.94	9.03	9.33	9.33	10.49
Seal Leakage	Outer	0.40	0.40	0.40	0.40	0.41	0.41	0.42
	Inner	0.41	0.41	0.41	0.41	0.42	0.42	0.42
Total		31.23	28.63	28.63	28.93	26.58	26.58	33.47
Outer Primary Zone		24.65	21.08	21.08	20.24	20.91	20.91	24.45
Inner Primary Zone		45.61	45.23	33.58	33.94	35.07	35.07	45.01
Combustor Total		100.00	100.00	100.00	100.00	100.00	100.00	

a) Included in Outer Primary Zone Airflow
b) Included in Inner Primary Zone Airflow

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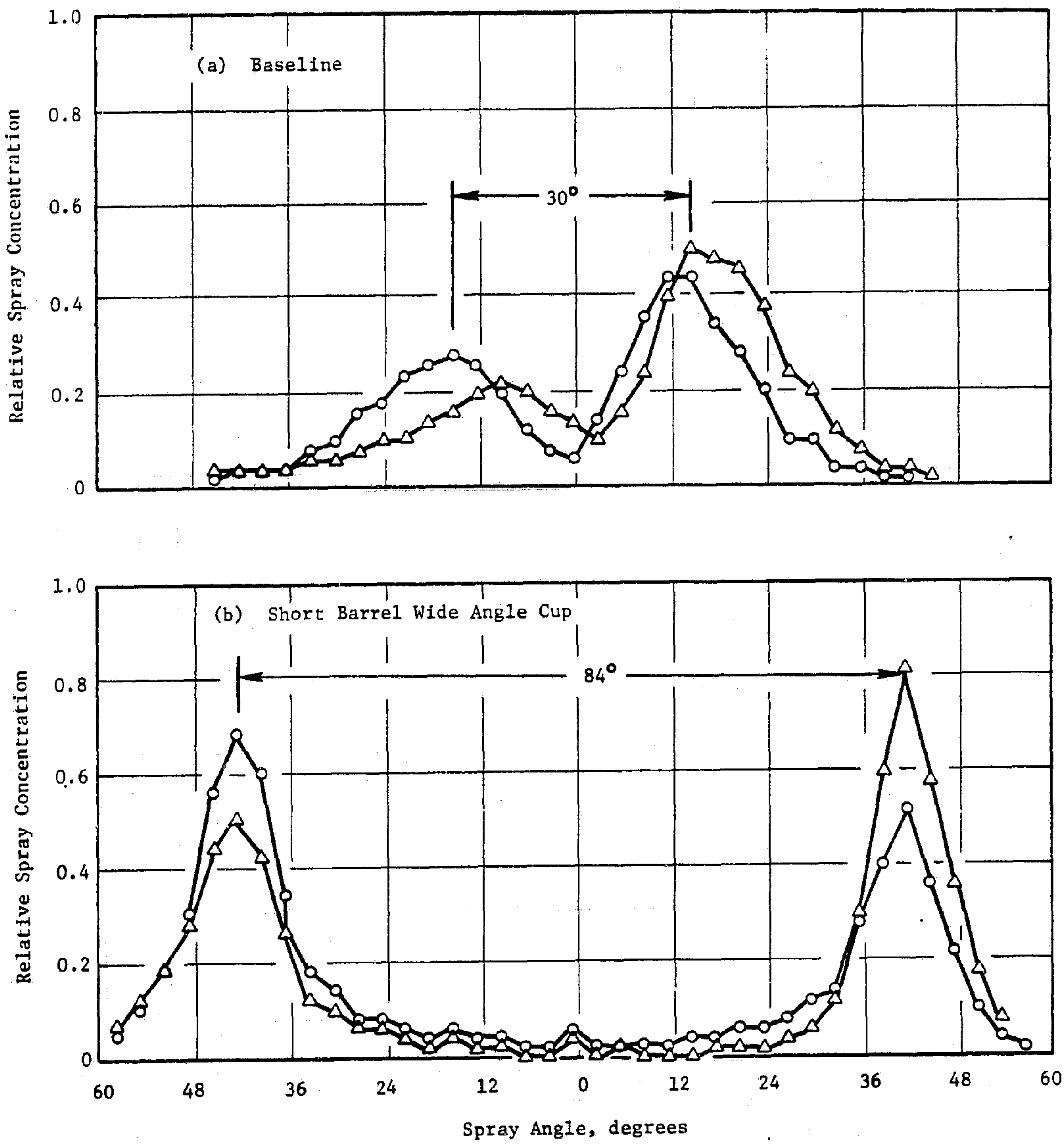
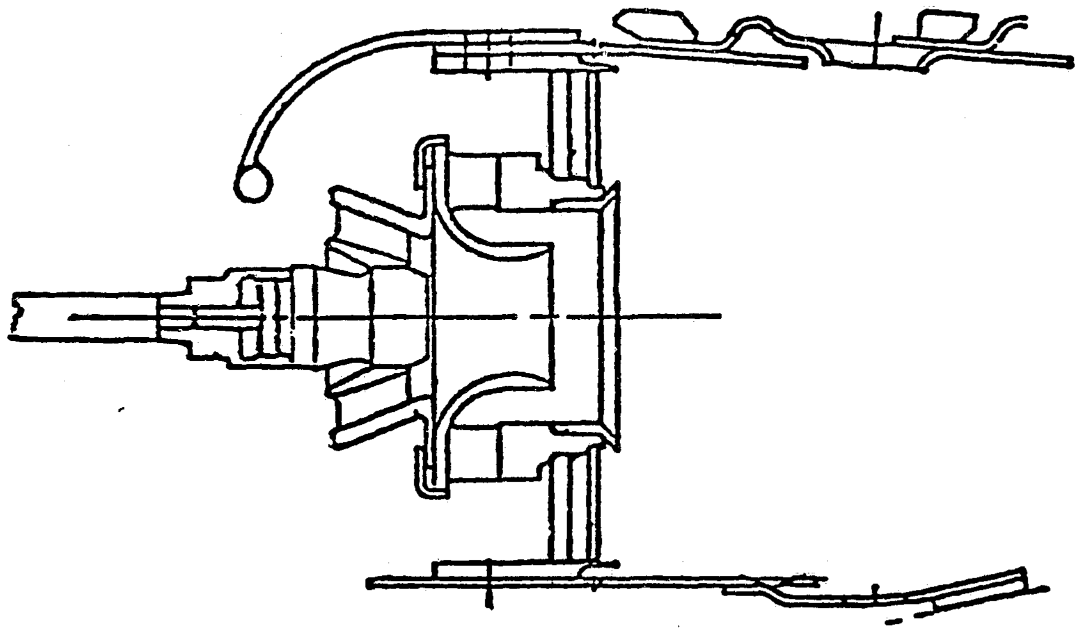
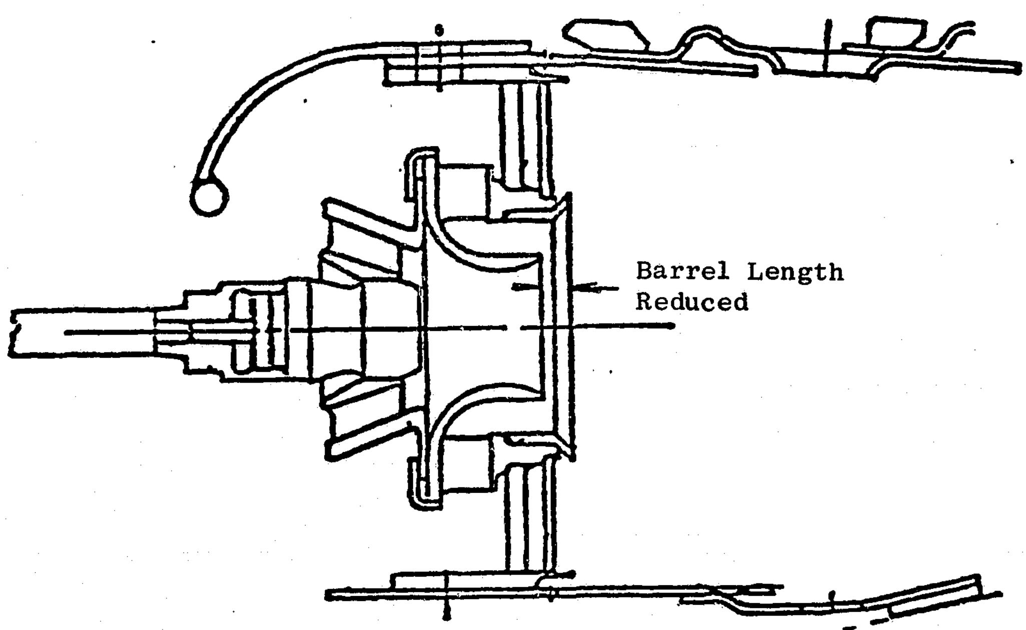


Figure 4-14. Double-Annular Pilot Stage Swirl Cup Patternation.



Baseline Swirl Cup



Modified Swirl Cup

Figure 4-15. Double-Annular Combustor Pilot Stage Swirl Cup Modification.

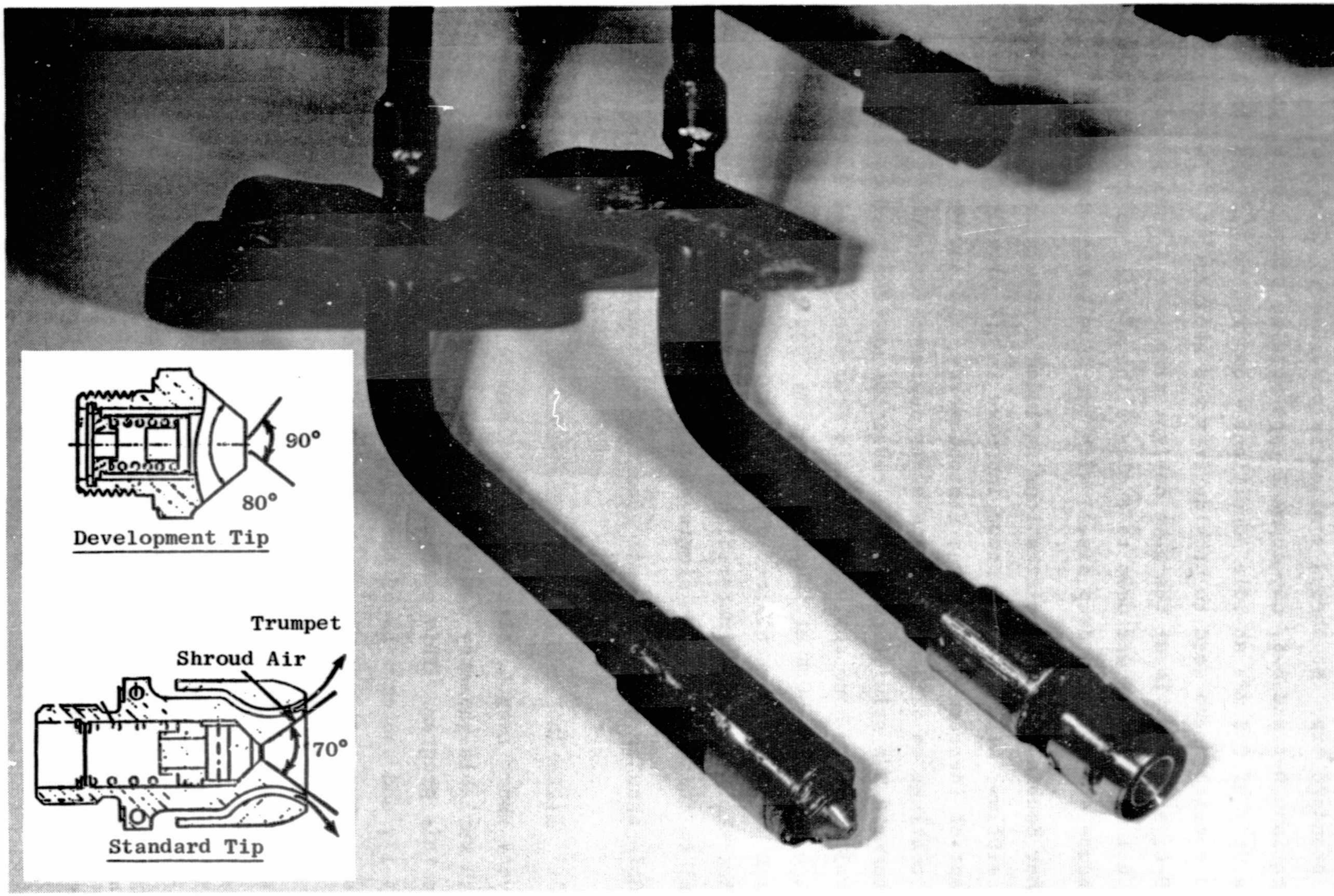


Figure 4-16. Double-Annular Combustor Pilot Stage Fuel Nozzles.

pressure atomizing nozzle having a nominal fuel spray of 90°, compared to the 70° standard tip. No shroud airflow is provided in this design. In Configurations D-4 and D-5, development type nozzles sized for a fuel pressure drop of 0.8 mPa at idle conditions (compared to 0.2 mPa for the standard nozzle), were used to provide improved atomization. In Configuration D-6, a larger tip of the same design, sized for a fuel pressure drop of 0.1 mPa at idle was used to evaluate the effects of reduced injector pressure drop (larger drop sizes) with the development tip design.

Other double-annular modifications included a reduction in main stage swirler airflow, with a simultaneous increase in aft dilution, to evaluate the effect of increased main stage stoichiometry, and the use of thermal barrier coatings on all internal combustor surfaces to reduce liner temperatures. The main stage airflow reduction was designed to in- crease the overall primary zone equivalence ratio from the original design value of about 0.6 to about 0.8 at takeoff operating condition, so lean combustion was in fact maintained even with this "richer" dome modification. The thermal barrier material used on the double-annular concept was identical to that used in the single-annular combustor.

Double-annular combustor test results are described in Section 4.2.

4.3.3 Ultra-Short Single-Annular Combustor With Variable Geometry

A very short length, high space rate, single-annular combustor concept with variable-geometry dome swirlers was selected as the third concept for this program. This combustor design concept is illustrated in Figure 4-17, and photographs of the combustor are shown in Figure 4-18. Relative to the single-annular combustor, combustion chamber length is reduced by 25% and volume is reduced by nearly 40%. Variable-area dome swirlers are used in this concept to control the combustor dome stoichiometry and dome velocity at various operating conditions. At engine idle and low power operating conditions, the variable swirler vanes are closed. In this mode, the design intent is to provide a swirl cup equivalence ratio near unity, and dome velocity of about 7.6 m/s at the idle conditions. These values are nearly the same as those used in the pilot

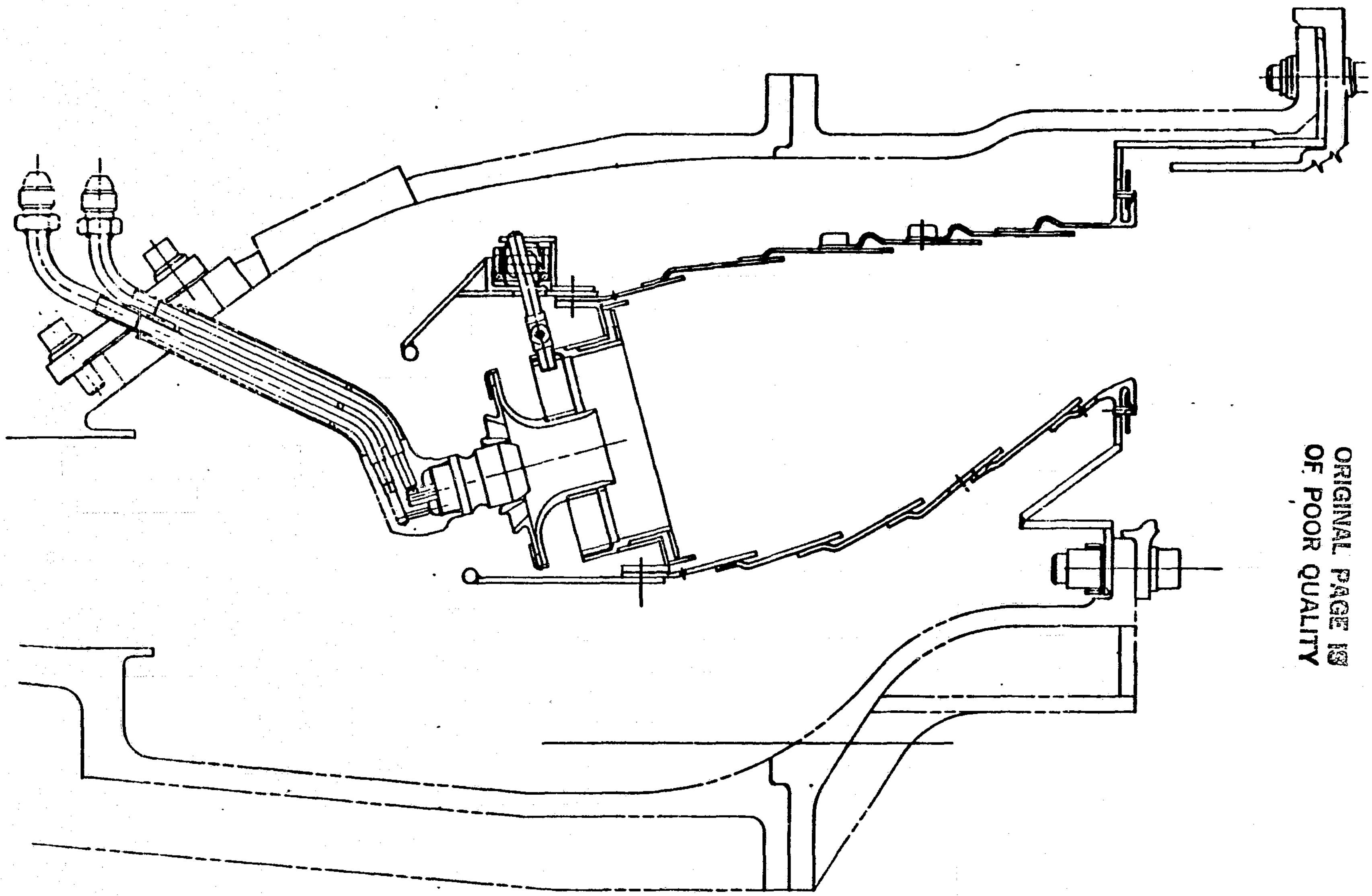


Figure 4-17. Variable-Geometry Combustor.

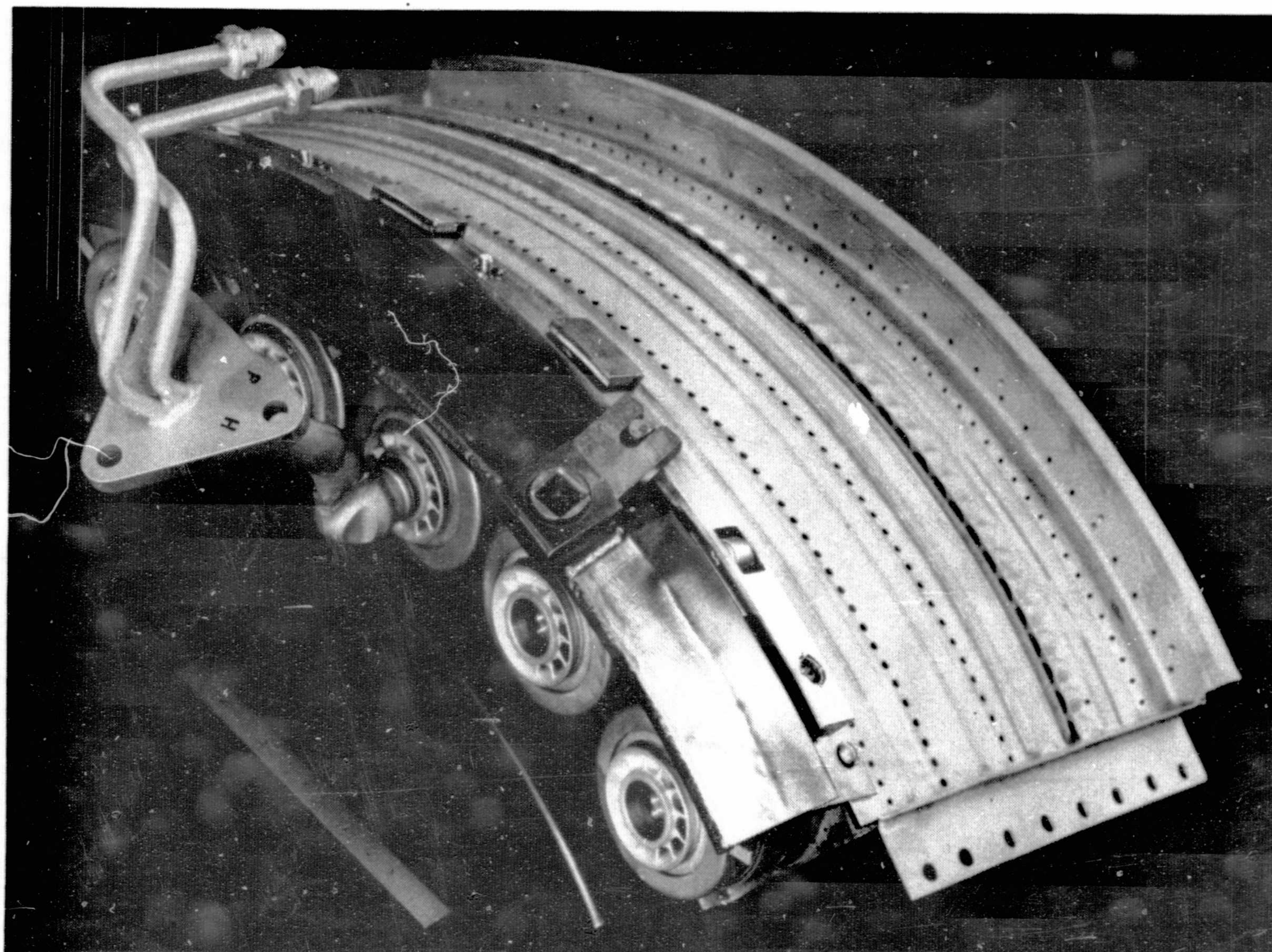


Figure 4-18. Phase I Variable-Geometry Sector-Combustor.

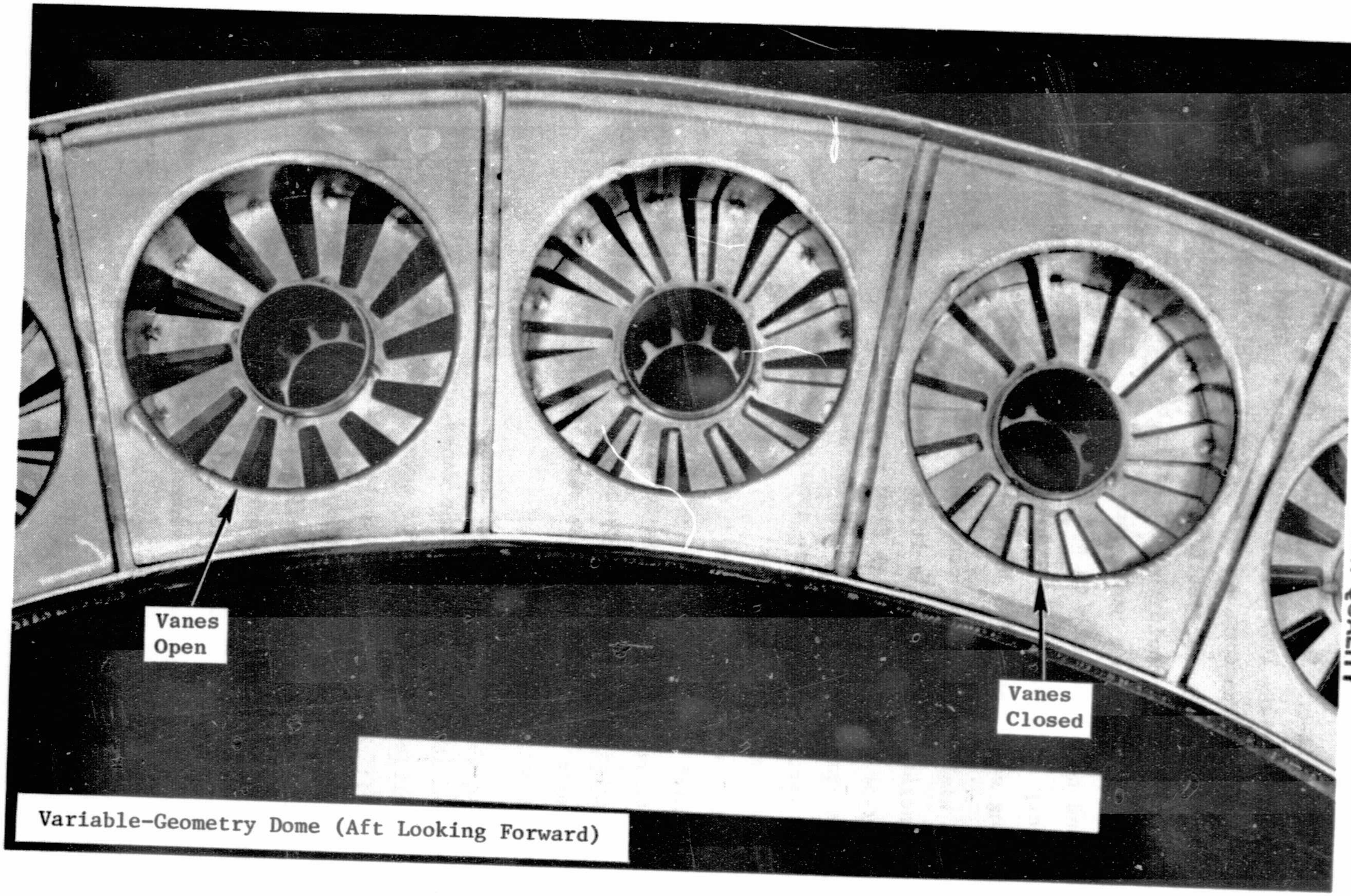


Figure 4-18. Phase I Variable-Geometry Sector-Combustor (Concluded).

stage of the double-annular combustor. In the baseline design, the combustion system pressure loss was predicted to be about 9.8% of the inlet total pressure with the dome swirlers closed. This relatively high pressure drop results in higher jet flow velocities, providing improved primary zone mixing which could theoretically be used to improve idle performance. On the other hand, dome and liner cooling flows are increased and tend to quench CO and HC reactions. The low dome velocity and relatively rich dome stoichiometry provide high development potential for obtaining very low CO and HC emissions at low power.

At the high engine power conditions, the variable swirler vanes are opened to increase the design swirler airflow level to about 50% of the total combustor flow. This high flow results in a dome equivalence ratio of about 0.6 for the baseline combustor design, and increased the dome velocity to about 19 m/s at these conditions. These values are similar to double-annular main stage levels. This high dome velocity and the short burner length result in very small values for burning residence time, which, combined with the lean burning, provide potential for very low NO_x and smoke emissions levels at the high engine power conditions and very low sensitivity of liner temperatures to fuel hydrogen content. The design pressure loss with the dome swirlers open is less than 5% of combustor inlet total pressure.

This variable-geometry combustor concept can be operated in a discrete, two-position mode, where the vanes are closed for all operations up to some specified power level (for example, approach power), and are opened for all operations above that level. Alternatively, continuous actuation can be used, where the opening is continuously varied depending on power level. Continuous actuation enables primary zone stoichiometry to be optimized over the entire operating range, at the cost of increased complexity. With the two-position mode, positive mechanical stops can be used to precisely position the vanes in the open or closed position. A drawback with the two-position mode is that successful intermediate power performance may not be obtained if the combustor is truly optimized for idle (vanes closed) and takeoff (vanes open). Performance at the extreme

high and low power conditions will have to be compromised to some extent to obtain acceptable midrange emissions and combustion efficiency. Whether discrete or continuous variable geometry is used, it is desirable to completely open the vanes at the lowest possible power level in order to avoid operation with increased combustor pressure drop.

The variable-geometry combustor is a relatively high risk concept because of the very compact envelope, high space rate, and, in particular, because of the added complexity of the variable area swirl cups. The swirler design used in the Phase I program is illustrated in Figures 4-19 and 4-20. Swirler flow is varied by rotating the secondary swirler vanes relative to a fixed register plate mounted at the vane exit. The variable vanes are mounted on the primary swirler venturi and are driven through a cowl supported unison ring which engages a drive pin at each cup location. The unison ring is driven by a drive rod and lever.

The register plate type swirler design was chosen for its simplicity and adaptability for continuous airflow modulation. Only one moving part is required for each swirler. In addition, the swirler bearing surfaces are not exposed to radiation heating from the combustion chamber. The secondary swirler was selected for the variable area feature so that the variable swirler could be fixed and a conventional "floating" primary swirler could be used to allow for differential thermal expansion of the swirler and fuel nozzle assemblies. Primary swirler airflow is supplied continuously to assist fuel atomization and protect against fuel nozzle carboning. With the close tolerance fits required in these variable area swirl cups and associated actuation linkages, prevention of binding is of primary concern. The design features shown in Figure 4-19, which include (1) stellite uniballs in the swirler drive unison ring, (2) a triballoy wear coating at the variable swirler/venturi interface to provide low friction, and (3) carbon graphite rollers to suspend the unison ring were, therefore, specified. Aerodynamically, the register plate type swirler design is well suited to continuous variable geometry since the flow is metered at the trailing edge of the swirl vanes in all vane positions, from full open to full closed. Therefore, the full combustor pressure

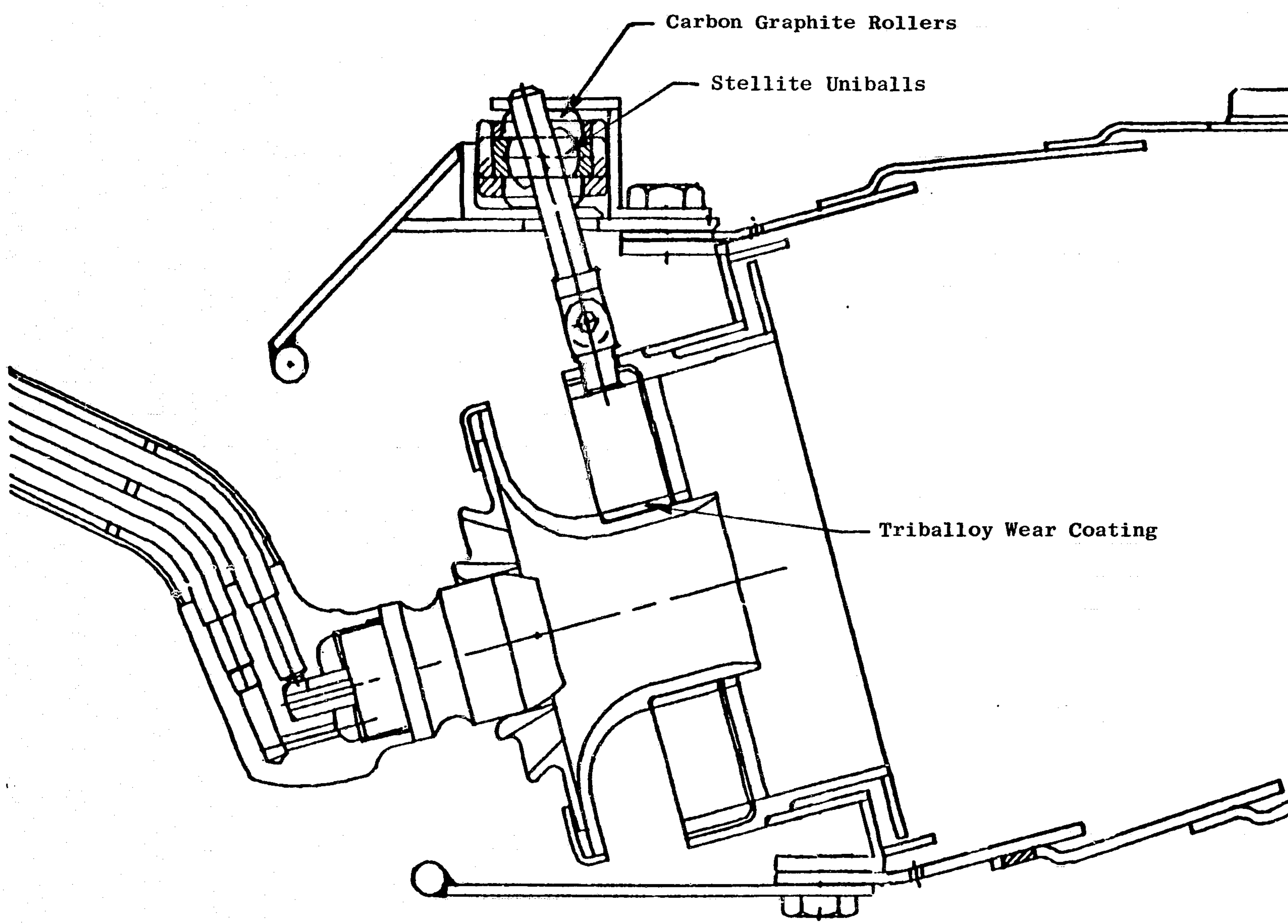


Figure 4-19. Variable-Geometry Materials.

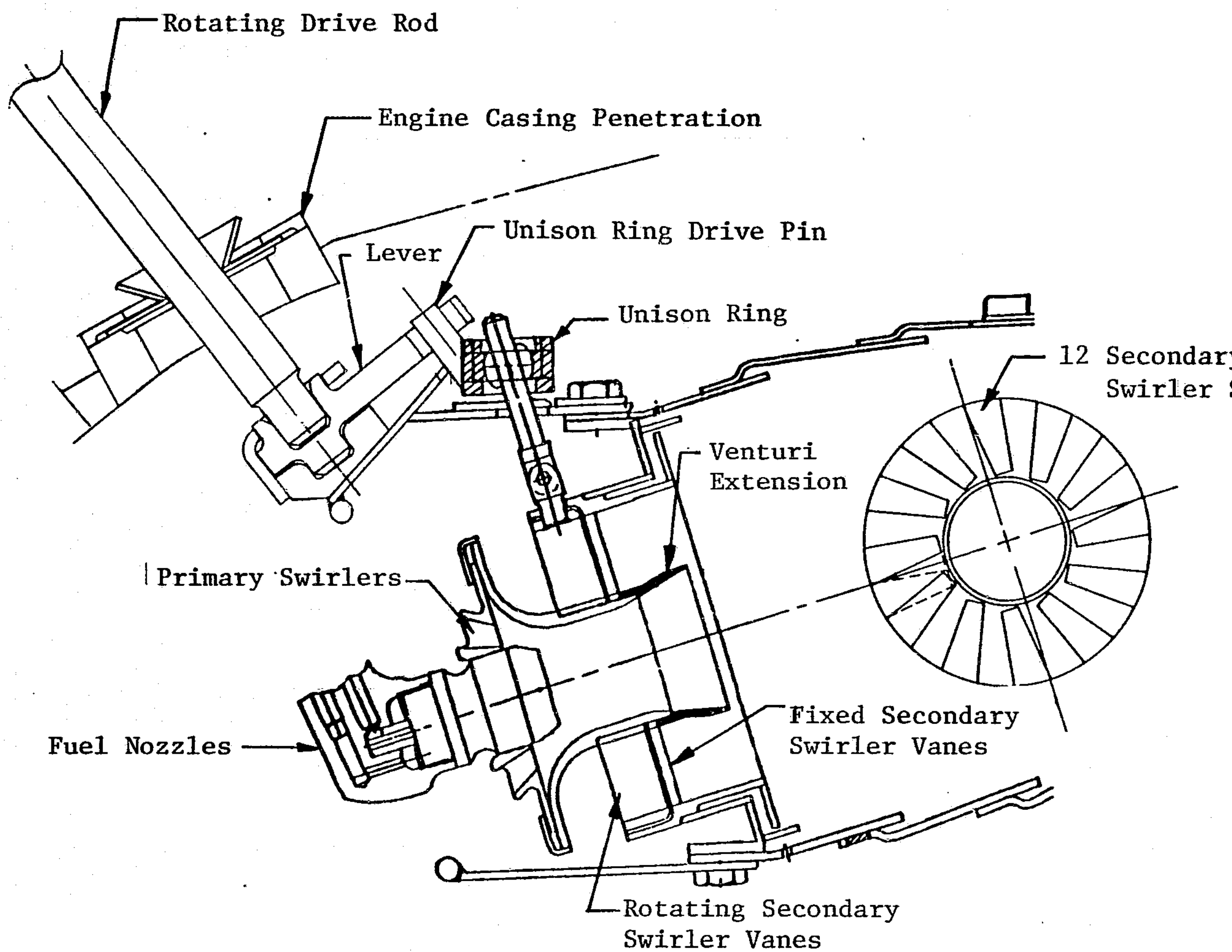


Figure 4-20. Variable-Geometry Mechanism.

drop is used most effectively in all positions. The baseline variable geometry combustor used CF6-50 dual orifice type fuel injector tips.

A total of nine different variable geometry combustor configurations were evaluated. The key modifications incorporated into each of these configurations are described in Table 4-8, and flow distributions for each configuration are presented in Table 4-9. Several different combustor flow distribution modifications were evaluated. Key combustor stoichiometry values and pressure loss levels for these modifications are compared to the design and baseline combustor values in Table 4-10. As indicated in this table, the primary zone equivalence ratio in the baseline combustor was leaner than the design value at idle due to greater-than-anticipated air leakage with the vanes closed. At takeoff, the primary zone equivalence ratio was richer than the design value and pressure drop was increased due to a lower-than-expected effective area of the baseline swirler in the open position. Configuration V-2 incorporated primary dilution to correct stoichiometry and pressure drop to the design levels at takeoff. This primary dilution was positioned in line with the swirl cups to reduce high fuel/air ratios measured downstream of and in line with the swirl cups in baseline tests.

Configuration V-3 investigated the effects of compensating variable geometry. In this scheme, variable area dilution is opened when the dome swirlers are closed, thereby eliminating the increased pressure drop effect at low power conditions. Benefits of using compensating geometry include reduced specific fuel consumption and increased compressor stall margin at low power, and potential for reduced CO and HC emissions since dome and liner cooling flow levels are not increased at low power. As shown in Table 4-10, swirler stoichiometry was increased to the original design value in this configuration, and idle pressure drop was reduced to the normal design value of 4.7%. Compensating variable dilution in Configuration V-3 was simulated by fixed dilution, so the takeoff values (shown in brackets), do not represent actual design points.

Configurations V-4 through V-8 all incorporated reduced authority variable geometry in which the swirler flow and pressure loss variation is less than in the original design. This modification involves a trade-off

Table 4-8. Variable-Geometry Combustor Modifications.

Modification	Intent	Configuration[(a)]								
		V-1	V-2	V-3	V-4	V-5	V-6	V-7	V-8	V-9
Baseline		(X)								
Primary dilution	Improved primary zone mixing leaner primary zone		(X)	X	X	X	X	X	X	
Compensating dilution at idle	Reduced idle pressure drop			(X)						
Reduced authority variable geometry	Reduced idle pressure drop				(X)	X	X	X	X	
Swirler venturi extension	Improved spray distribution				(X)	X	X	X	X	
Reduced dome cooling	Reduced quenching of CO and HC at idle					(X)	X	X	X	
Reduced liner cooling (forward panels)	Reduced quenching of CO and HC at idle					(X)	X			
High pressure simplex fuel nozzles (low power)	Improved atomization at low power						(X)	X		
Thermal barrier coatings	Reduced liner temperatures							(X)	X	
Increased primary dilution	Improved primary zone mixing								(X)	
High pressure simplex fuel nozzles (high power)	Improved atomization at high power								(X)	
Fixed Geometry Simulation	Improved Mixing at High Power									(X)

(a) (X) = Primary modification(s) under evaluation in specified configuration.

X = Modifications retained from previous configurations.

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Table 4-9. **Variable-Geometry Combustor - Flow Distributions.**

Location			V-1	V-2	V-3	V-4	V-5	V-6	V-7/8	V-9	Design
			Flow, Percent of Total Combustor Airflow								
VANES OPEN											
Swirl cups	- nozzle shroud		1.7	1.6	1.2	1.5	1.5	1.5	1.5	--	1.6
	- swirler		45.0	42.0	33.4	30.8	30.8	30.8	30.8	24.0	49.9
Dilution	- outer liner	panel 0	--	--	--	--	--	--	1.4	--	--
		panel 1	--	3.8	3.1	3.7	3.7	3.7	3.7	7.0	--
		panel 3	15.3	14.2	11.3	13.9	13.9	13.9	13.9	3.0	12.8
		panel 4	--	--	20.4	12.5	17.1	7.2	7.2	--	--
	- inner liner	panel 0	--	--	--	--	--	--	--	--	--
		panel 1	--	3.2	2.6	3.1	3.1	3.1	3.1	--	--
		panel 3	11.3	10.5	8.3	10.3	10.3	10.3	10.3	7.0	10.4
		panel 4	--	--	--	--	--	--	5.3	3.0	--
Cooling	- outer liner		11.2	10.4	8.3	10.2	9.0	9.0	10.2	--	10.3
	- dome		6.5	6.0	4.8	5.9	3.4	3.4	3.4	--	6.1
	- inner liner		8.0	7.4	5.9	7.2	6.3	6.3	7.2	--	8.0
	- leak		1.0	0.9	0.7	0.9	0.9	0.9	0.9	--	0.9
Total combustor			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
VANES CLOSED											
Swirl cups	- nozzle shroud		2.4	2.1	1.6	1.9	1.9	1.9	1.9	--	2.7
	- swirler		24.3	21.9	16.3	14.6	14.6	14.6	14.6	--	15.3
Dilution	- outer liner	panel 0	--	--	--	--	--	--	1.7	--	--
		panel 1	--	5.1	3.8	4.6	4.6	4.6	4.6	--	--
		panel 3	21.1	19.2	14.2	17.1	17.1	17.1	17.1	--	21.6
		panel 4	--	--	25.6	15.5	21.2	21.2	8.9	--	--
	- inner liner	panel 0	--	--	--	--	--	--	1.4	--	--
		panel 1	--	4.3	3.2	3.8	3.8	3.8	3.8	--	--
		panel 3	15.5	14.2	10.6	12.7	12.7	12.7	12.7	--	17.5
		panel 4	--	--	--	--	--	--	6.5	--	--
Cooling	- outer liner		15.4	14.0	10.4	12.5	11.0	11.0	12.6	--	17.5
	- dome		8.9	8.1	6.0	7.3	4.2	4.2	4.2	--	10.3
	- inner liner		11.0	9.9	7.4	9.0	7.9	7.9	8.9	--	13.4
	- leak		1.3	1.2	0.9	1.0	1.0	1.0	1.1	--	1.8
Total combustor			100.0	100.0	100.0	100.0	100.0	100.0	100.0	--	100.0

Table 4-10. Variable-Geometry Combustor Airflow Modifications.

Configuration	Swirl Cup Equivalance Ratio	Primary Zone Equivalance Ratio*		Combustor Pressure Loss, % P_3		Swirl Cup Flow, % W_3	
	Idle	Idle	T/O	Idle	T/O	Idle	T/O
Design	0.91	0.70	0.62	9.8	4.7	14.2	42.0
V-1 Baseline	0.64	0.54	0.68	8.3	5.3	20.3	38.1
V-2 Primary Dilution	0.70	0.45	0.63	7.1	4.7	18.4	35.5
V-3 Compensating Dilution	0.88	0.57	[0.79]	4.7	[3.2]	14.6	28.2
V-4 Reduced Authority	1.00	0.58	0.80	6.0	4.5	12.9	26.3
V-5/V-6 Increased Primary Dilution, Reduced Authority	1.00	0.61	0.83	6.0	4.5	12.9	26.3
V-7/V-8	1.00	0.55	0.78	6.0	4.5	12.9	26.3
V-9 Fixed Geometry Swirler	-	-	0.78	-	4.5	-	19.6

*Swirl Cup + Primary Dilution + 1/2 Dome Cooling Flow

between high power emissions and performance and intermediate power performance. The primary zone equivalence ratio at takeoff is increased, although relatively lean burning is still maintained. At intermediate power, performance is improved with the richer primary zone. Implementation of this reduced authority scheme involved a 25% reduction in swirler flow area. Aft dilution was increased to make up for this reduction in dome airflow. Configurations V-7 and V-8 retained the limited authority variable geometry, and primary dilution was increased slightly to improve primary zone mixing.

Configuration V-4 also incorporated a primary venturi extension and an increased fuel nozzle immersion, as illustrated in Figure 4-21. These modifications were identified in spray patternation tests as shown in Figure 4-22. Before the extension was added, the fuel spray spread out at a very wide angle when the swirl vanes were closed at low power. Under these conditions, much of the fuel impinged on the combustor dome and liner surfaces or gathered in the cooling film where combustion is inefficient. With the insert, a narrower, more stable, spray angle was obtained with the vanes closed. Spray patternation tests with the vanes open (high power mode) indicated that the spray angle was increased relative to the baseline swirler.

Dome and forward liner cooling flows were reduced to decrease quenching of CO and HC at idle in Configuration V-5. Aft dilution was increased to retain the design combustor pressure drop.

High pressure simplex fuel nozzles were used to evaluate improved fuel atomization at low power (Configuration V-6) and at high power (Configuration V-8). The radial air shroud shown in Figure 4-23 was used with these nozzles.

Configuration V-8 incorporated the same type of thermal barrier coating as was used in the other combustor concepts and also featured redistributed aft dilution for profile trim. In previous configurations, dome cooling and swirler airflow had been reduced, and this airflow had been added to aft panel outer dilution for convenience. In Configuration

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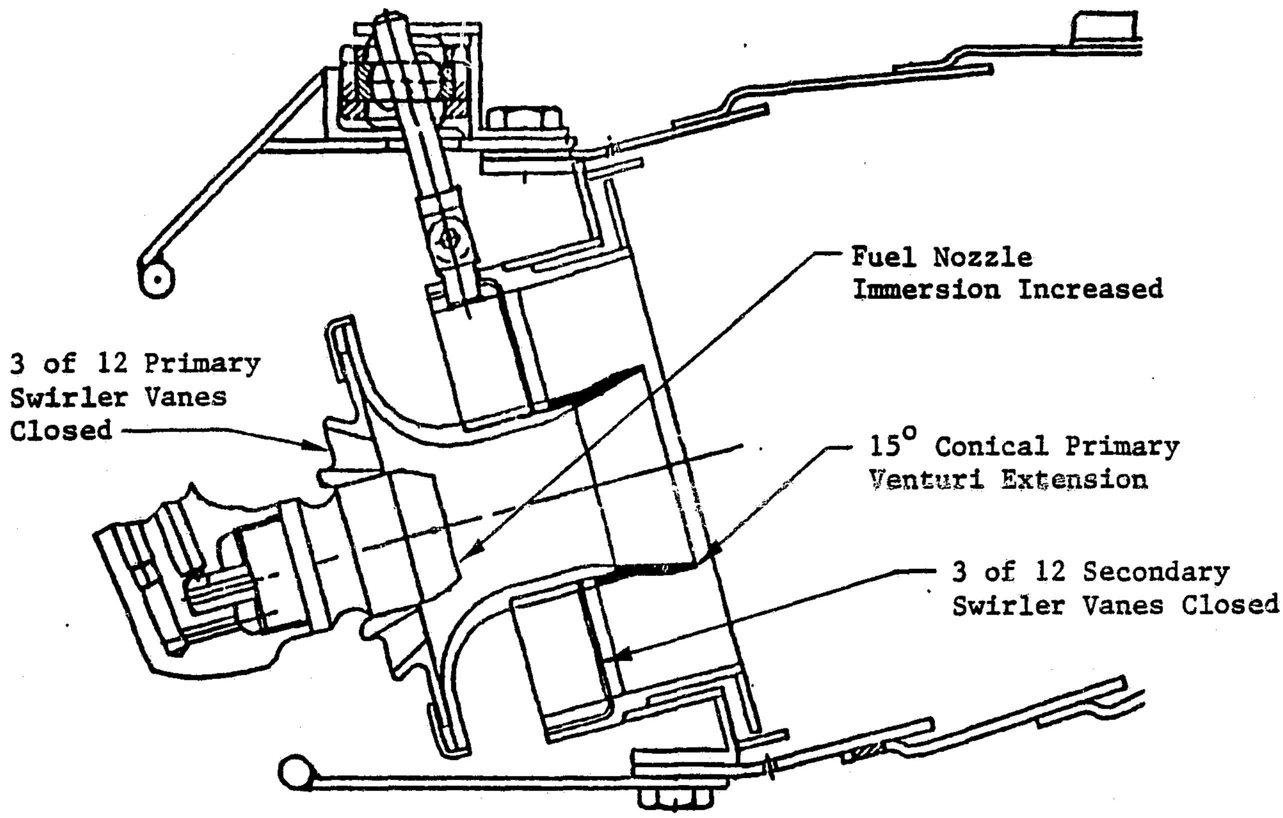

Figure 4-21. Variable-Geometry Swirler Modifications.

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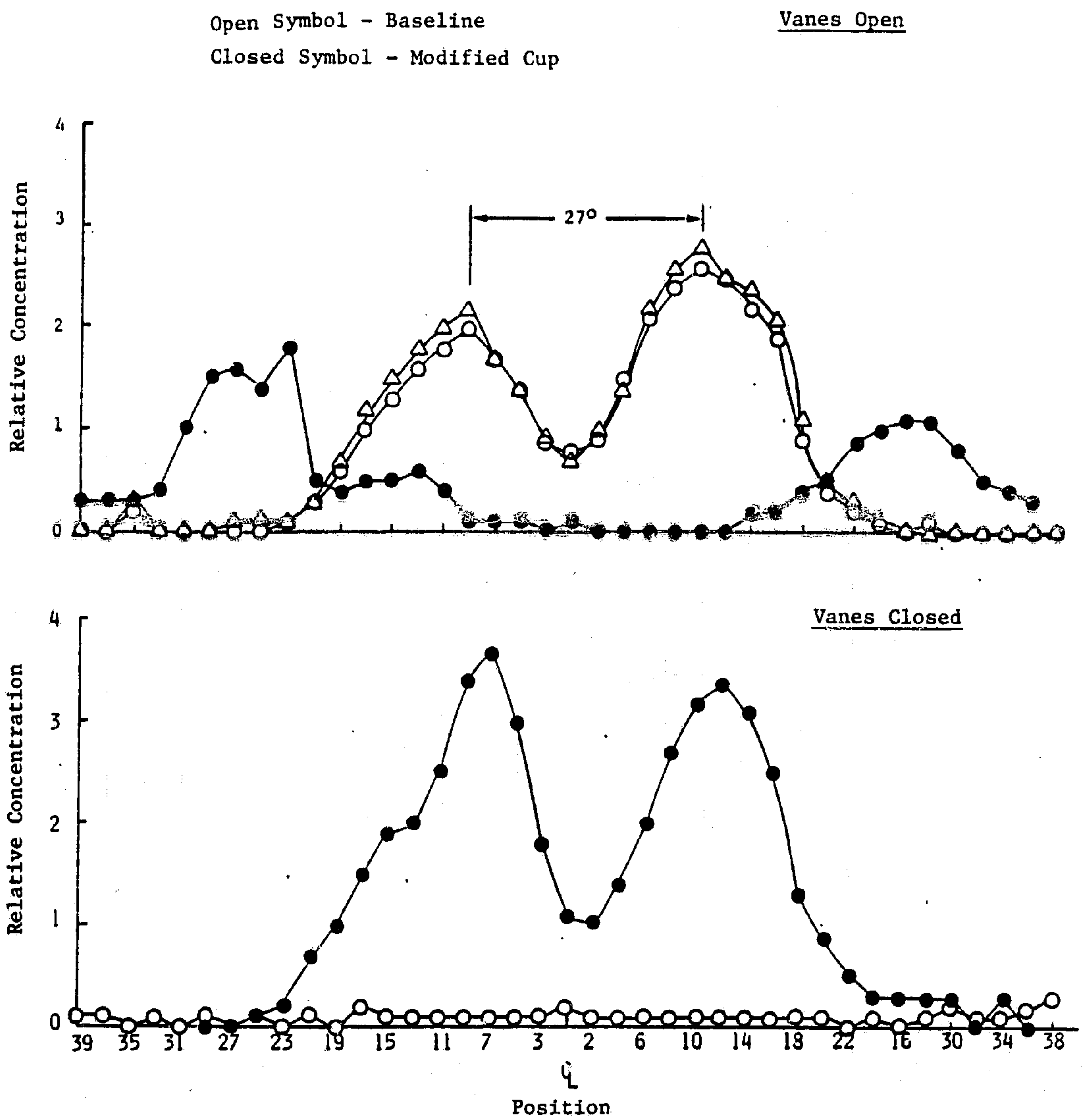

Figure 4-22. Variable-Geometry Swirler Patternation.

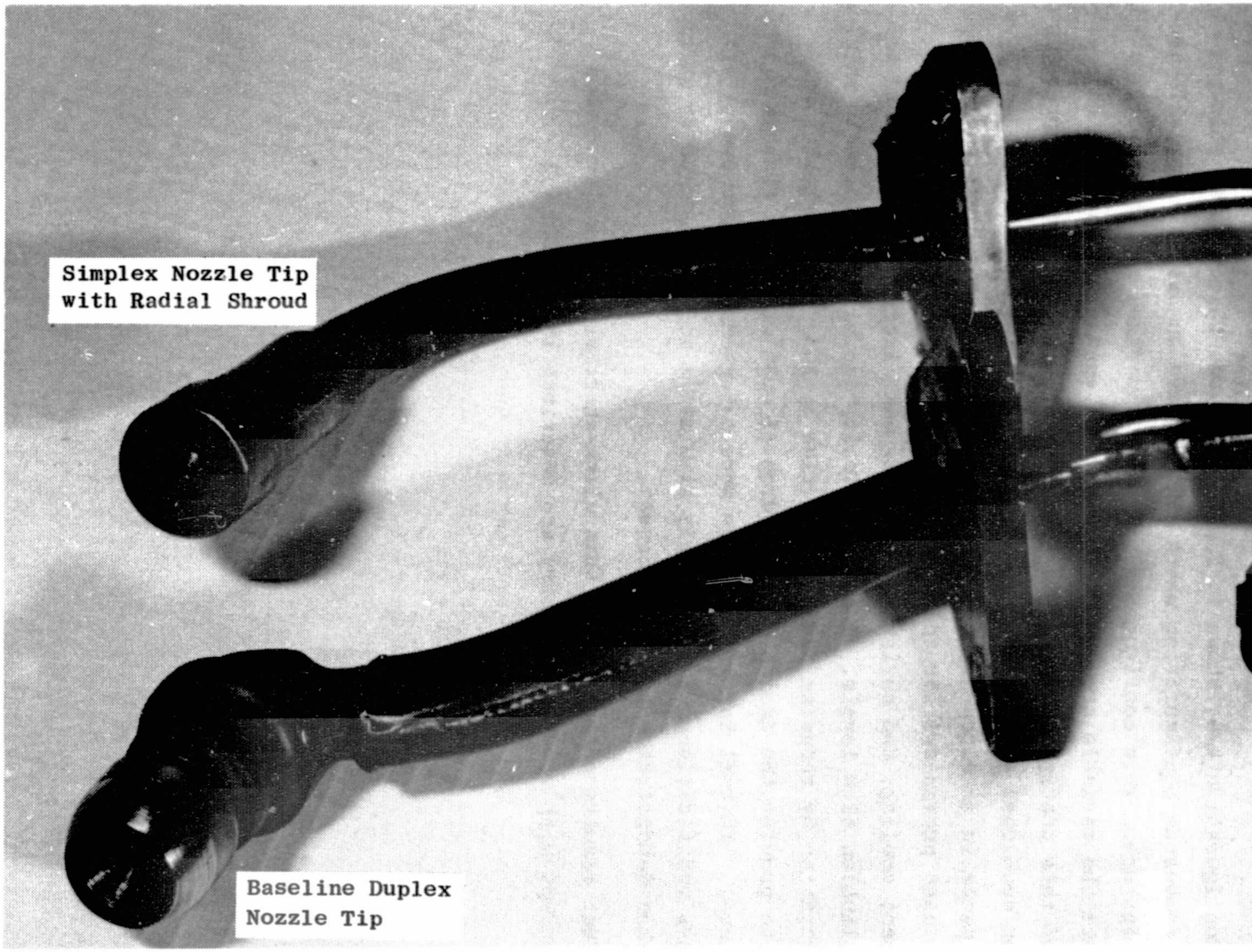

Figure 4-23. Variable-Geometry Combustor Fuel Nozzles.

V-8, a portion of this dilution flow was moved to aft panel inner dilution to improve the exit temperature profile.

Configuration V-9, shown in Figure 4-24, was the only variable-geometry combustor configuration which did not have an operable variable-geometry feature. This configuration incorporated fixed geometry swirlers to simulate the variable area swirl vanes in the open position. The objective of this configuration was to simulate a combustor which had previously been developed at General Electric to provide low smoke levels and good performance in an ultra-high temperature rise application. This configuration used proven swirler and low pressure fuel injector designs, impingement cooling, and revised flow splits with increased cooling and primary dilution flow levels. The dome velocity was also increased in this configuration by reducing combustor airflow by 20%. The combustor was sized to provide the design pressure drop of 4.5% with this reduced airflow level. Thermal barrier coatings were not used. The purpose of all of these modifications was to closely simulate a previous combustor design which had demonstrated low smoke levels.

Test results obtained with this ultra-short single-annular combustor concept with variable geometry are described in Section 6.3.

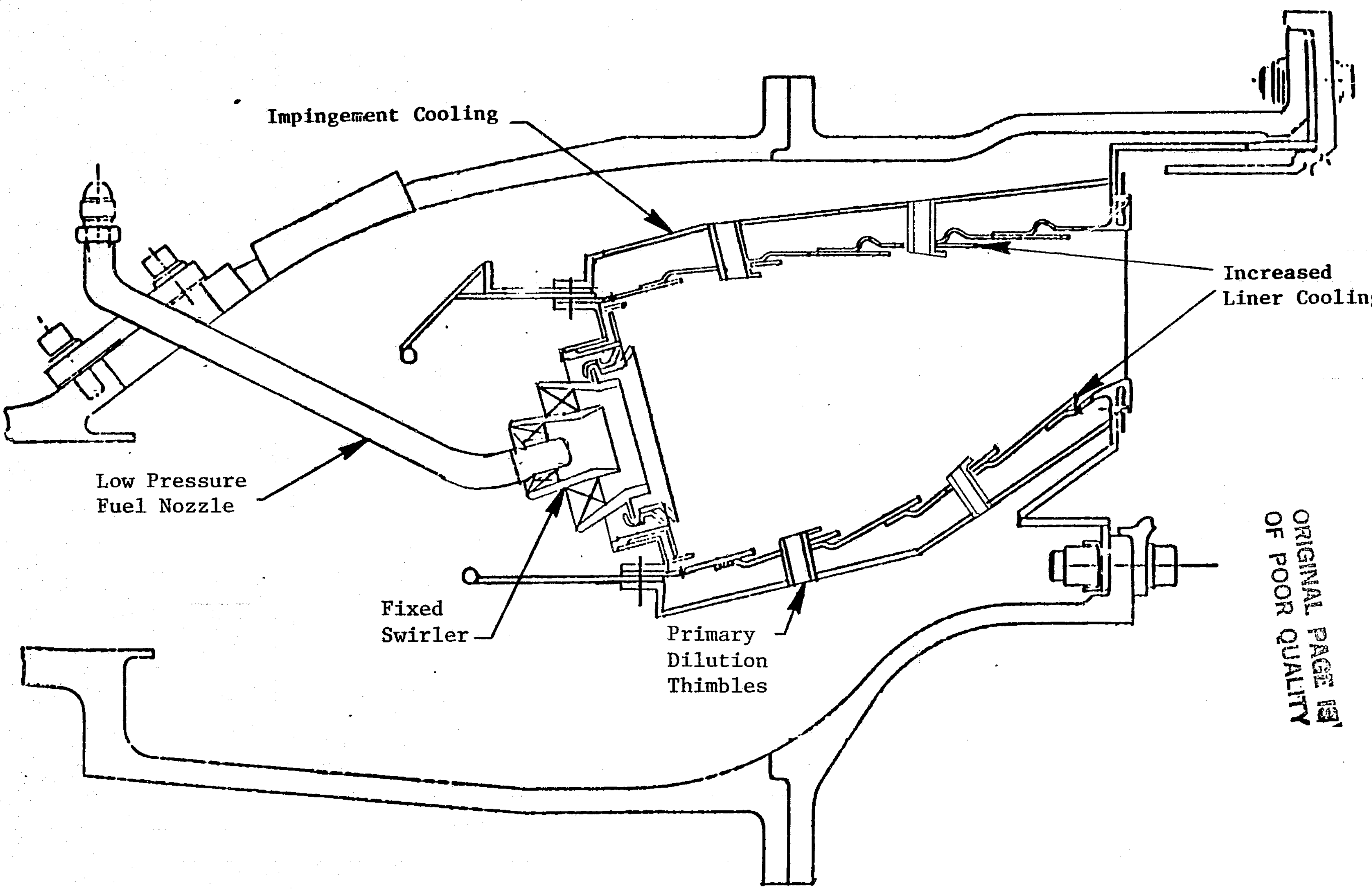

Figure 4-24. Variable-Geometry Configuration V-9 Modifications.

5.0 COMBUSTOR DEVELOPMENT APPROACHES

The 25 different combustor configurations described in the previous chapter were experimentally evaluated in a series of 27 test runs, described below.

5.1 TEST RIG AND FACILITIES

All of the full scale tests were conducted in a five swirl-cup sector combustor test rig capable of operation at actual engine conditions, including pressures up to 4.1 MPa as well as subatmospheric pressures representative of altitude windmilling operation. This test rig exactly duplicates a 1/6 sector (60°) of the CF6-80 engine annular combustor flowpath. The test rig assembly drawing is shown in Figure 5-1. The sector combustor flowpath is mounted within a high pressure casing. The pressure casing is a cylindrical section, sized to mate with the test cell high pressure inlet plenum. Several bosses are provided on this shell for spark ignitor mounting, bleed airflow extraction, and fixed test rig instrumentation. The downstream flange of the pressure shell is designed to mate with an exit transition piece which contains all required water-quench apparatus. All combustor services, including fuel supply lines, torch ignitors, liner instrumentation, and exit rake lines are led out through openings in a service spool, which is sandwiched between the pressure shell and transition piece (Figure 5-2). The aft end of the transition piece is designed to mate with a 25.4 cm, 4.1 MPa high temperature discharge control valve.

The CF6-80A engine combustor casing flowpath is cantilevered on a flowpath mounting bulkhead in the test rig. An access plate is provided in this bulkhead to permit removal of combustor fuel nozzles from the forward end of the rig. Air enters the combustor flowpath through a rounded inlet. After passing through a short constant area section, the airflow passes through a diffuser which simulates a 60° sector of the CF6-80 engine design. The flow exiting this diffuser passes through the sector test combustor dome and liners.

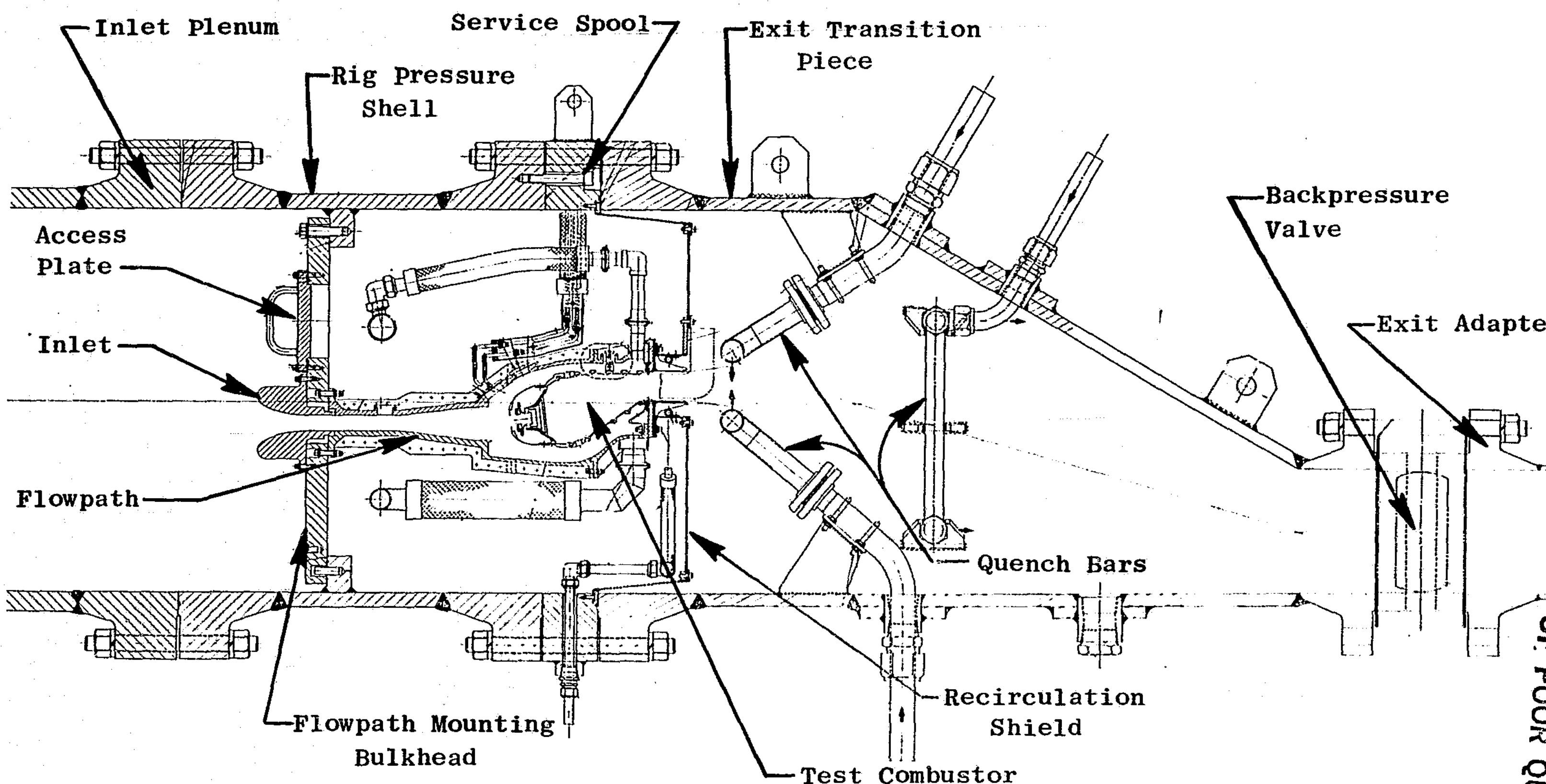

Figure 5-1. High Pressure Sector Test Rig.

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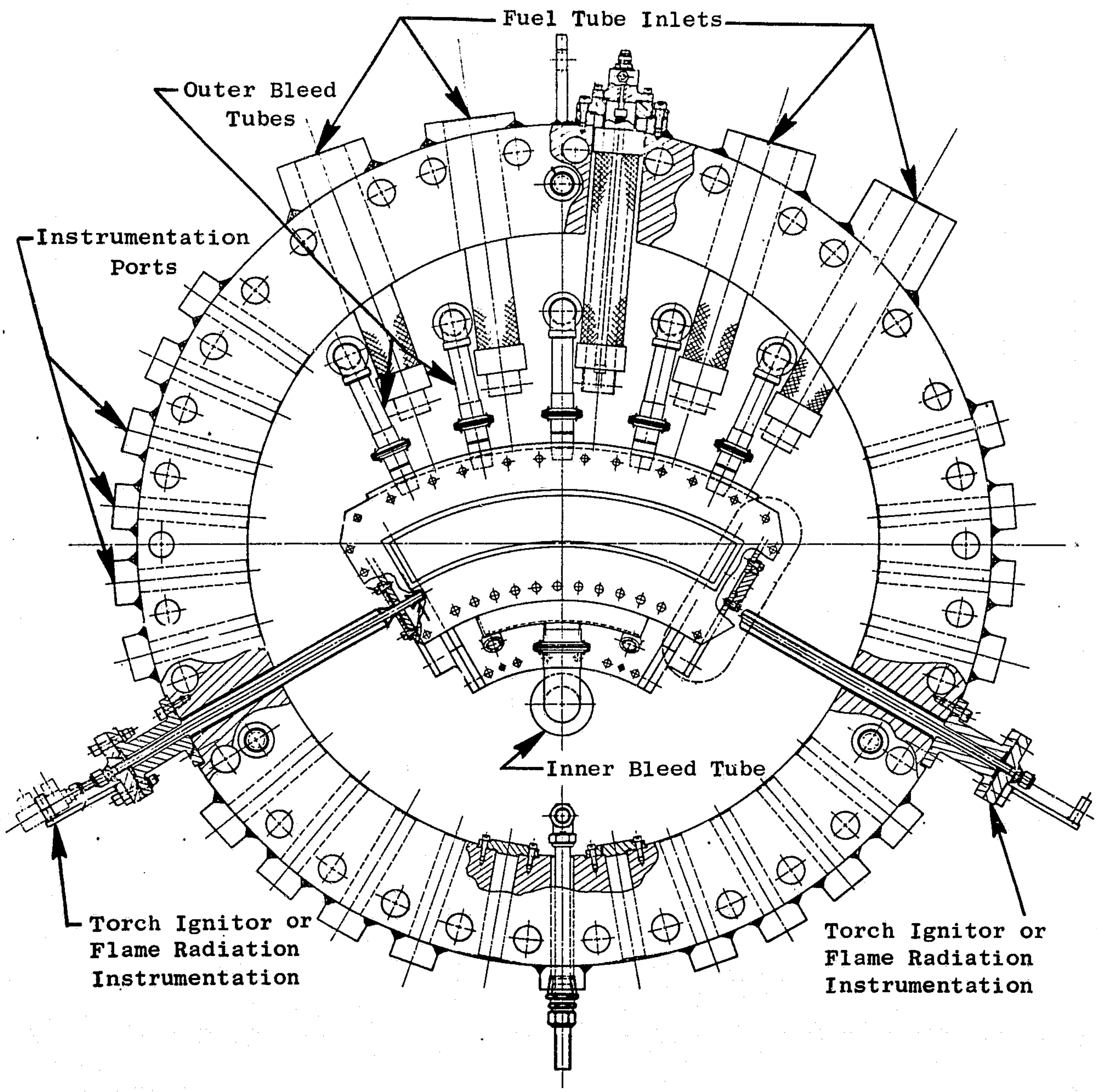

Figure 5-2. Five Swirl Cup Sector-Combustor Test Rig.

Sidewall cooling of the sector combustor test hardware is accomplished by impingement/film cooling. The cooled sidewalls (Figure 5-3) are bolted directly to the combustor liners to minimize leakage. The sector combustor test hardware is aft-mounted, as in the CF6-80A engine design. Sidewall cooling flow is equivalent to about 5% of total combustor airflow (2.5% on each side). This cooling airflow is fed through the combustor inlet diffuser along with combustor and bleed airflows. Although sidewall cooling enters the combustor, it is not counted as combustor airflow. Total rig airflow and bleed flow are actually measured. Sidewall cooling flow is assumed to be a fixed percentage of total rig airflow which is calculated from cold flow calibration data from tests of the sidewalls and combustor.

The combustor exit rakes are mounted in a water-cooled instrumentation section located immediately downstream of the combustor exit. A pliable recirculation shield extends from this instrumentation section to the wall of the pressure shell to prevent recirculation of the quench water upstream of the combustor exit plane.

All of the Phase I program sector test evaluations were conducted in the Cell A3 test facility located at Evendale, Ohio. This facility contains all of the inlet ducting, exhaust ducting, fuel and air supplies, and controls and instrumentation required for conducting combustor component tests.

The cell itself is a rectangular chamber with reinforced concrete blast walls and a lightweight roof. The installed ventilation and safety equipment is designed specifically for tests involving combustible fluids. The piping is arranged to accommodate two test vehicles simultaneously. Effective test cell utilization is realized by mounting test vehicles on portable dollies with quick-change connections as shown in Figure 5-4 so that buildup operations are accomplished in another area and a test vehicle occupies the cell only for the duration of its actual testing. Control consoles and data monitoring equipment are located in an adjacent control room.

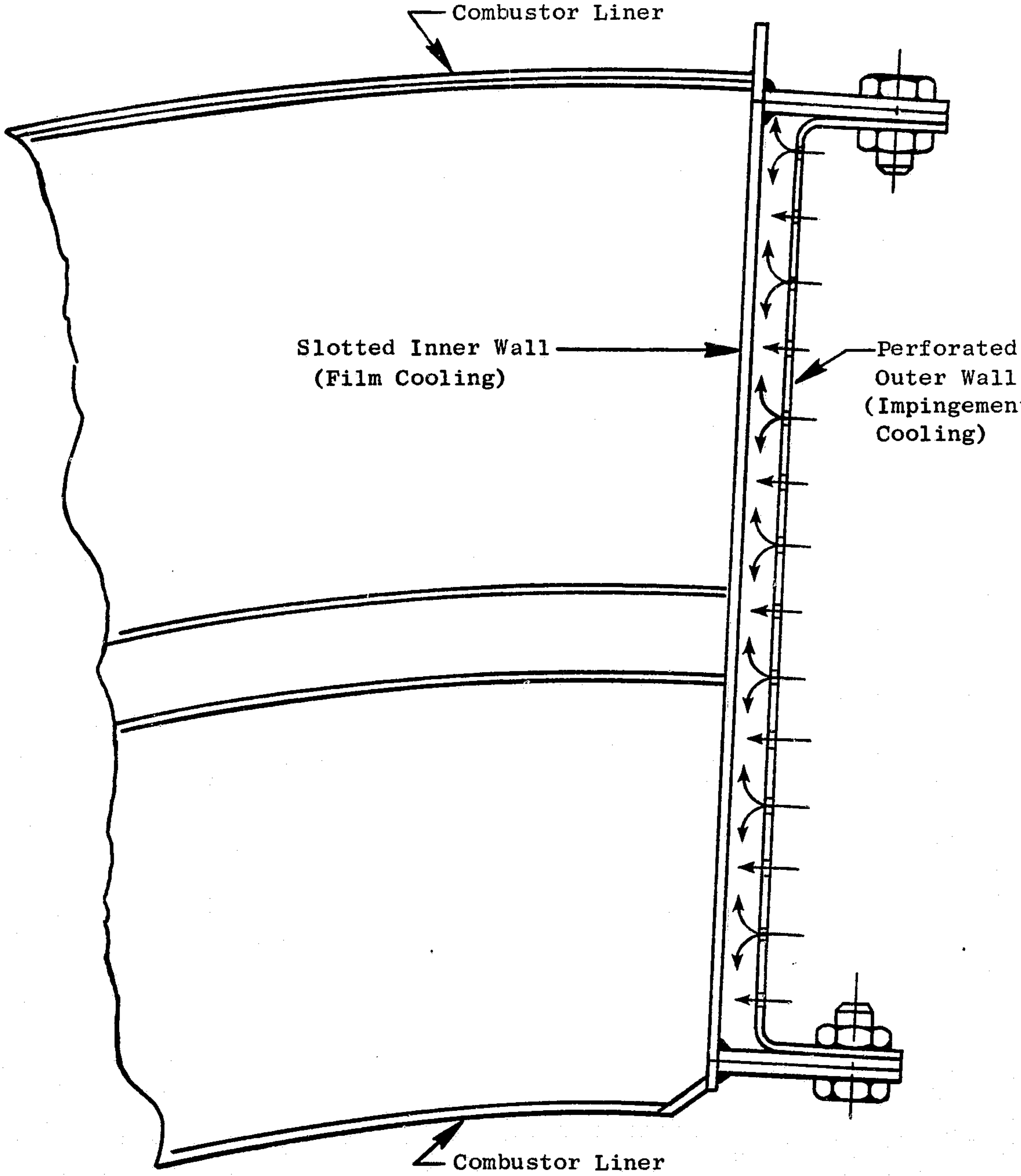

Figure 5-3. Sector Sidewall Construction.

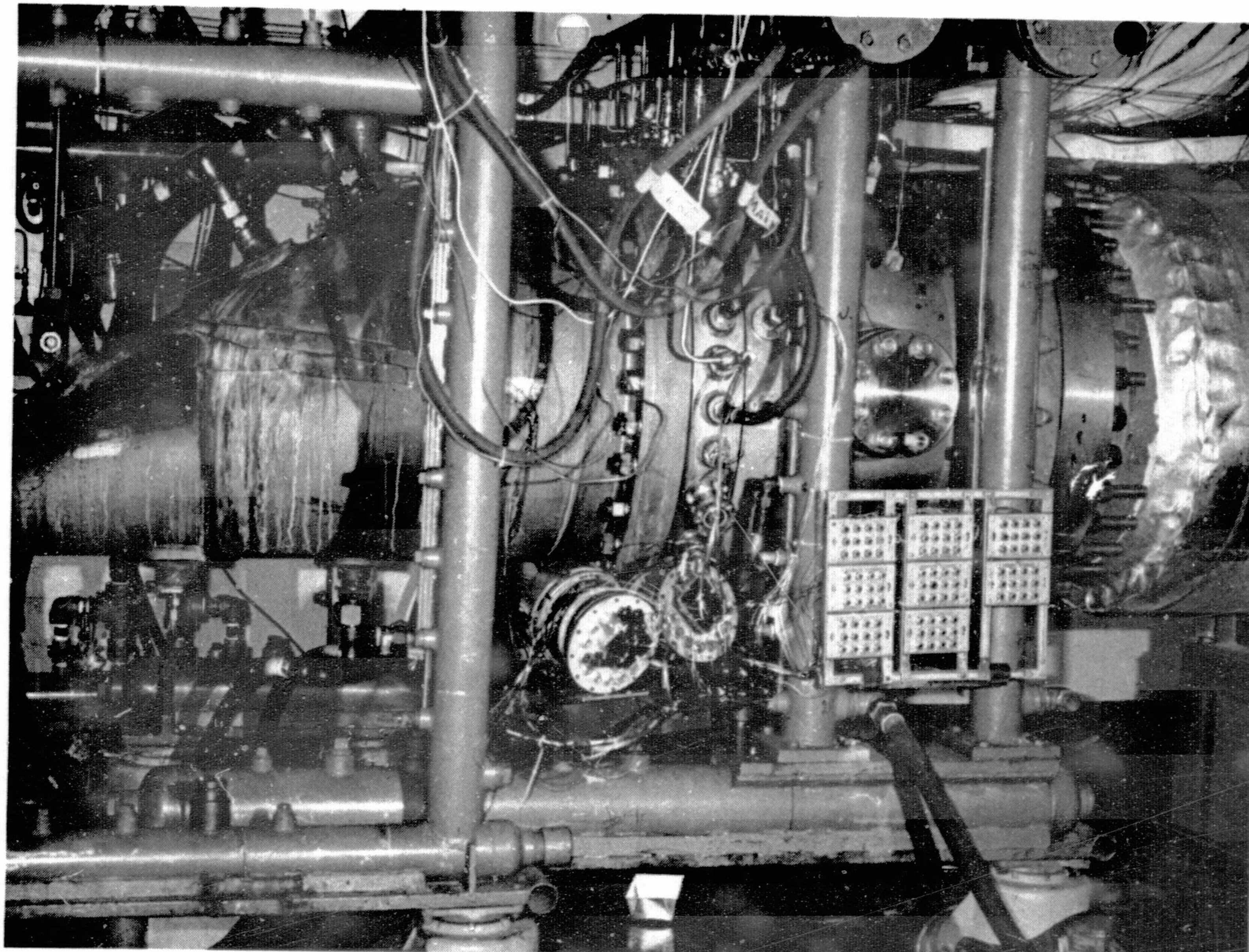

Figure 5-4. CF6-80A Five-Cup Sector-Combustor Test Rig Installed in Test Cell.

Air can be supplied to this facility by either of two separate air supply facilities. The major air supply system utilized during this program is a newly constructed system with an airflow capacity of 34 kg/sec at 4.1 MPa. This new facility has its own indirectly fired preheater so that nonvitiated air can be supplied at temperatures up to 920 K. Using this air supply facility, the five-cup sector-combustor rig has been tested at the actual engine sea level takeoff condition. A second air supply system with a nominal capacity of 45.4 kg/sec of continuous airflow at 2.07 Mpa delivery pressure is also available. The compressors in this second system can also be used for test cell exhaust suction to achieve conditions corresponding to a pressure altitude of up to 22.9 km. This second system also has an indirectly fired preheater to provide nonvitiated air inlet temperatures up to 920 K.

Fuel is supplied to cell A3 from six bulk storage tanks. Three 114 M^3 tanks are currently used for JP-4, Jet-A, and ERBS fuels, while two of three 38 M^3 tanks are used for the special ERBS 11.8 and ERBS 12.3 fuels being used in this program. Fuel from each of these tanks is piped directly to Cell A3. The Cell A3 fuel system consists of boost pumps to provide fuel injection pressures up to 8.3 MPa and individual control and metering systems for two different fuel flows (pilot stage and main stage in the double-annular combustor - primary and secondary fuel nozzle orifices in the single-annular and variable-geometry combustors).

5.2 INSTRUMENTATION

The combustor and test rig were extensively instrumented to measure pertinent combustor operating conditions and emissions and performance data. A listing of the combustor parameters which were measured or calculated is presented in Table 5-1.

Main and verification total inlet airflow measurements are obtained using Standard ASME orifices which are an integral part of the Cell A3 facility. Diffuser inlet total pressure and temperature were measured with three combination pressure/temperature rakes based on the design shown in Figure 5-5. These rakes were mounted so that the individual

Table 5-1. Proposed Measured or Calculated Combustor Parameters.

Parameter	Symbol	Value Determined From
Inlet Total Pressure	P_3	Average of Measurements of Two elements on Three Rakes
Inlet Static Pressure	P_{S3}	Wall Static Taps
Exit Total Pressure	P_4	Average of Measurements of Four Elements on Four Rakes
Total Rig Airflow	W_c	ASME Orifice
Bleed Airflow	W_b	ASME Orifice
Combustor Airflow	W_c	Calculated From W_3, W_b, and Airflow Calibration Data to Correct for Sidewall Cooling
Total Fuel Flow	W_t	Turbine Flowmeter
Pilot Stage or Primary Fuel Flow	W_{fp}	Turbine Flowmeter, If More Than One Fuel Stage is Employed
Main Stage or Secondary Fuel Flow	W_{fm}	Turbine Flowmeter, If More Than One Fuel Stage is Employed
Pilot Stage Fuel Injector Pressure Drop	ΔP_{ft}	Fuel Injector Pressure and Combustor Static Pressure
Main Stage Fuel Injector Pressure Drop Fuel Inlet Temperature	ΔP_{fmf}	Measured in Fuel Manifold at Test Rig Inlet
Inlet Air Humidity	h	Dew Point Hygrometer
Inlet Total Temperature	T_3	Average of Measurements of Six Elements on Three Rakes
Exit Total Temperature	T_4	Average of Measurements of 12 Elements on Three Rakes
Pattern Factor	PF	T_4 Measurements
Profile Factor	PROF	T_4 Measurements
Combustor Metal Temperature (Maximum and Average)	T_L	A Minimum of 12 Liner Thermocouples
Total Radiation Flux	Q_r	Total Radiation Pyrometer
Metered Fuel/Air Ratio (Combustor)	f_m	Calculated from W_f and W_c
Fuel/Air Ratio (Gas Sample)	f_s	Calculated from Gas Composition
Combustion Efficiency (Combustor)	η_{tc}	Calculated from T_3, T_4, f_m
Combustion Efficiency (Gas Sample)	η_s	Calculated from Gas Composition
Smoke Number	SN	Average of 16 Elements on Four Rakes
Exhaust Gas Composition	CO, CO_2, HC, NO_x	Average of 16 Elements on Four Rakes
Emission Indices	EI	Calculated (ARP 1256 Equations)

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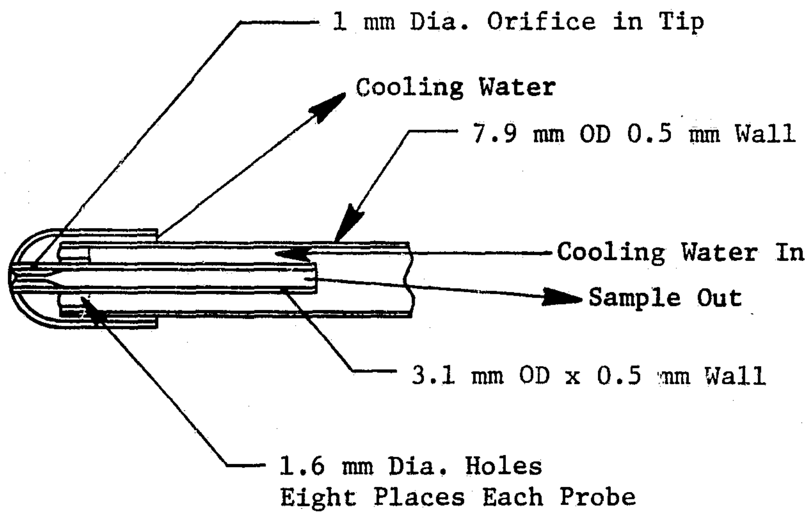

Pressure Sample Probe

Figure 5-5. Water Cooled Pressure/Gas Sample Probe Configuration.

elements are located at the axial plane of the leading edges of the compressor outlet guide vanes. Diffuser inlet static pressures were measured with two wall static taps located at this same axial position.

Main and verification total fuel flow rates were measured with turbine flowmeters. Additional flowmeters were used to measure individual primary and secondary fuel nozzle orifice, or pilot and main stage, fuel flows. Fuel flow rates were corrected for fuel viscosity and specific gravity, based on fuel analyses and the liquid temperature measured in the fuel manifold. A pressure tap in the fuel manifold was used in combination with dome internal static pressure to obtain fuel nozzle pressure drop.

Each test combustor was instrumented with an array of metal surface thermocouples for characterization of the different design concepts and fuel types. A minimum of 12 dome and liner thermocouples were used to obtain representative data. A typical combustor liner thermocouple installation is shown in Figure 5-6. Here, outer liner temperatures are measured at two circumferential locations (in line with and between cups) and three axial locations (forward, middle, and aft panels). All liner temperatures were measured adjacent to the three center swirl cups to avoid end effects. Figure 5-6 also illustrates the location of combustor internal static pressure taps and the use of temperature-sensitive paints to obtain temperature patterns.

The combustor exit plane was equipped with seven rakes to measure total pressure and total temperature and to extract gas samples. Each water cooled rake was equipped with either four thermocouple elements (shielded, 1 mm diameter Platinum - 6% Rhodium/Platinum - 30% Rhodium thermocouples) or four gas sample and total pressure elements. The thermocouple elements were designed with a short length (down to 5 mm) to enable reliable operation at the hot, high velocity, turbulent combustor exit flow conditions at high power. Experience has shown that longer elements experience a high rate of failure due to bending. The short thermocouple element design is accurate at high power conditions (conduction errors calculated to be less than 1%), but conduction errors are

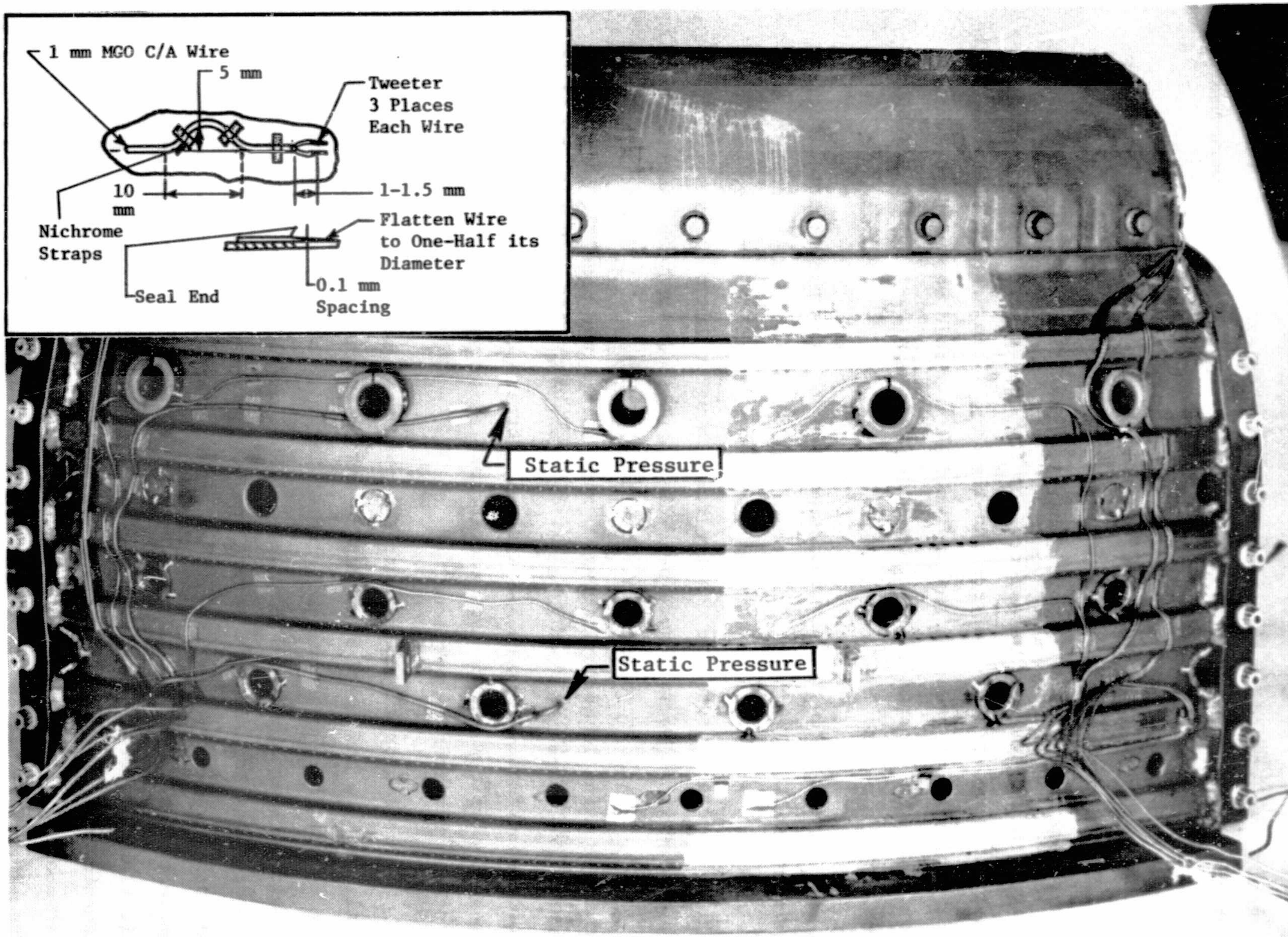

Figure 5-6. Typical Liner Thermocouple Installation.

larger (more than 5%) at idle conditions. The gas sample/total pressure lines were valved in such a way that, with the flow shut off, the total pressure could be read, and gas composition could be measured with the flow directed to the gas analyzers. The seven rakes were located as shown in Figure 5-7 with three rakes in line with the swirl cups and four rakes located between swirl cups. The end rakes were located 12° from the end walls (one full swirl cup spacing) in order to eliminate end wall cooling effects from the measured results. Valves in the gas sample lines permit either individual gas samples or manifolded samples to be analyzed. Individual samples were used to investigate radial and circumferential profiles of composition. Manifold samples of all elements of Rakes B, C, D, and E were used to obtain the overall or average gas sample composition. Special valves and manifolds having gradual bends to permit smoke sample acquisition were used in Rakes B and C. Ganged samples of these two rakes were normally used for smoke samples. The gas sample/total pressure/smoke probe tip was designed to provide the necessary quenching of the chemical reactions at the probe tip and incorporates simultaneous water cooling of the probe body and stems. The same rake design is used for exit temperature measurements except that noble metal thermocouples with flame-sprayed tips are used in the central duct of the probe.

Figure 5-8 shows the rakes mounted in the five-cup sector-combustor test rig. The tips of the probes are mounted at an axial plane corresponding to that of the leading edge of the turbine nozzle or stator.

The gas sampling lines from each probe tip are led individually to the emissions analysis equipment located adjacent to the test cell and are steam traced from the probes to the analyzers to maintain gas temperatures at about 400 K. Instrumentation to monitor the temperature of the sample lines is incorporated into this bundle.

Standard sample gas analysis equipment was used, including a flame ionization detector (FID) for measuring total HC concentrations, two non-dispersive infrared analyzers for measuring CO and CO_2, and a heated chemiluminescent analyzer for measuring NO. Continuous flow through the sampling lines was maintained by using three-way valves to divert each

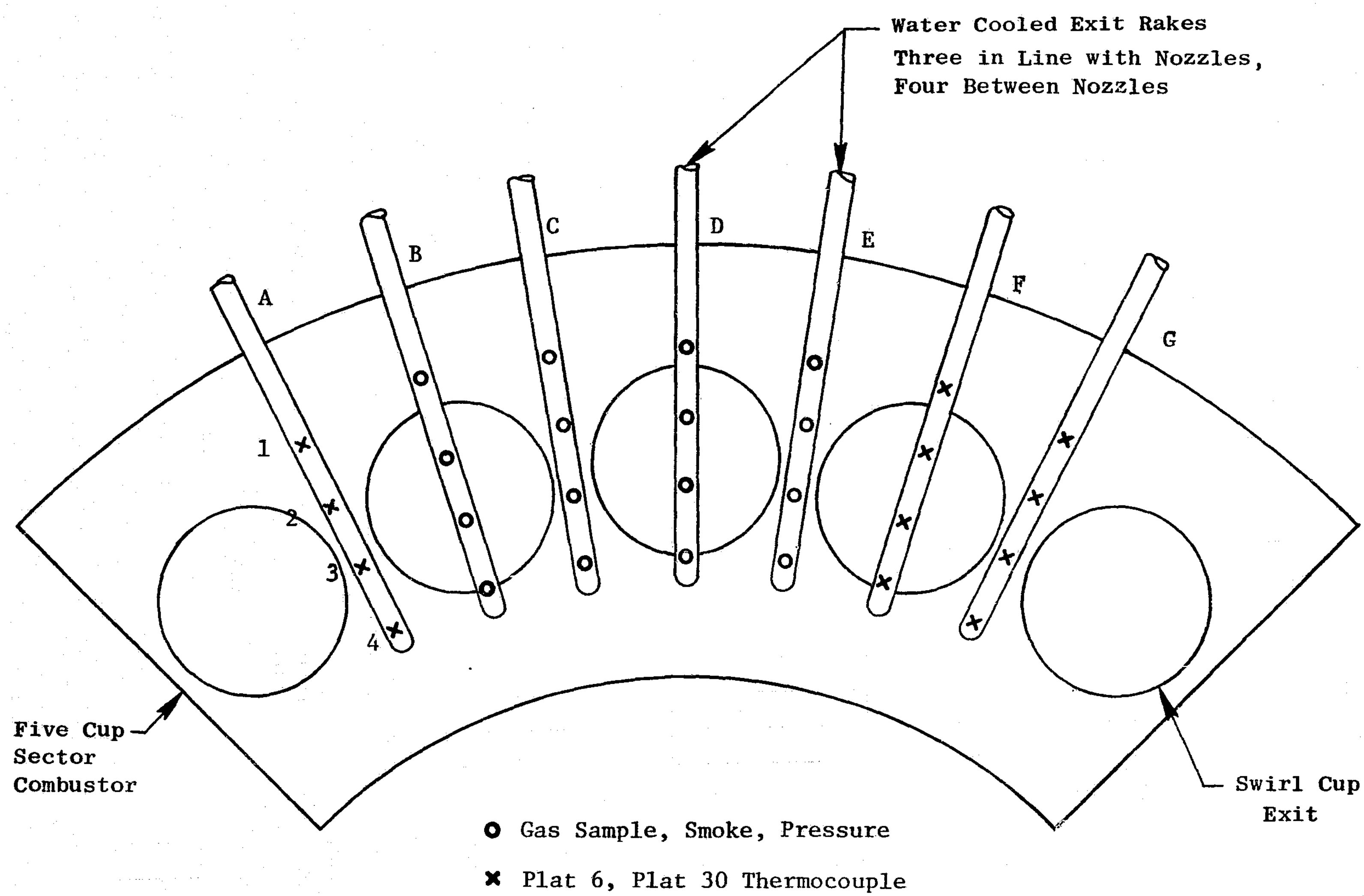

Figure 5-7. Combustor Exit Instrumentation.

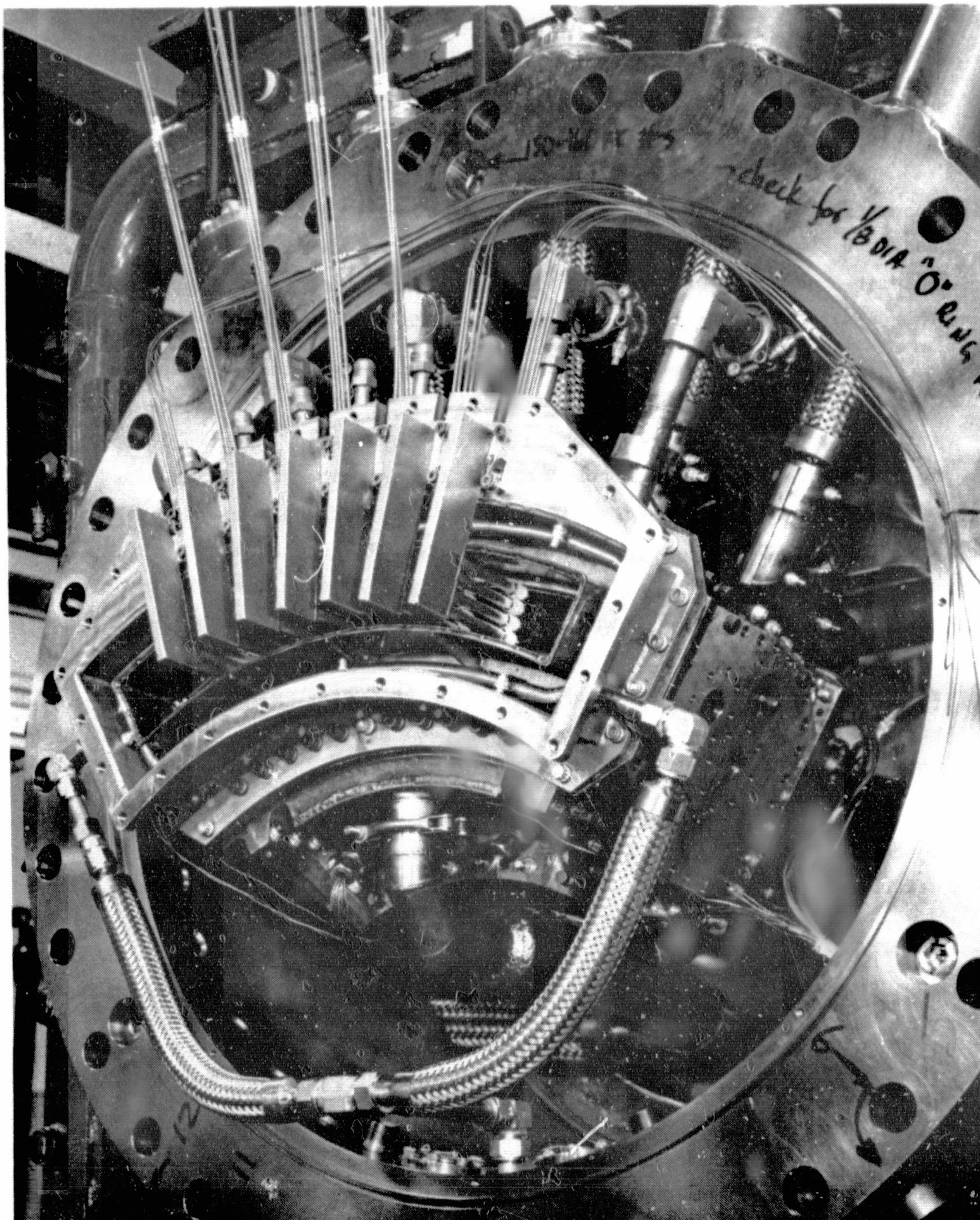

Figure 5-8. CF6-80 Combustor Exit Instrumentation Rakes Mounted in Five-Cup Sector-Combustor Test Rig.

given sample stream either to an overboard manifold or into the analysis units. This system conforms fully to the specifications of SAE ARP 1256 and to the EPA requirements (Reference 8).

Smoke levels were measured with the standard General Electric smoke measurement console. This unit contains a heated filter holder and the required pump, control valves, and flow metering devices, and features an automated sampling sequence for improved measurement reproducibility. This system conforms to SAE ARP 1179 and EPA requirements.

Flame radiation measurements were taken using a total radiation pyrometer (Honeywell Radiamatic Pyrometer Model RL-2). Measurements were taken in the primary zone where radiation levels were expected to be at a maximum. The signals were obtained using a sapphire rod "light pipe" approximately 0.3 mm in diameter with the interior end mounted flush with the sector-combustor sidewall inner surface. The sapphire rod was enclosed in a metal tube for support of the span between the test rig pressure shell and the combustor as shown in Figure 5-9. The tip of the rod was cooled and purged by air to prevent contact and contamination of the sapphire rod viewing surface by combustion products. A water-cooled mounting pad and air-cooled casing were used to maintain the pyrometer at room temperature.

The pyrometer sensing element is a thermopile which provides a direct current voltage output. The pyrometer/sapphire rod assembly was calibrated with a resistance-heated Inconel strip which was controlled by a Barnes Temptron pyrometer unit prior to use in the tests.

5.3 TEST FUELS

Properties of the four test fuels used in this program are presented in Table 5-2. The three Experimental Referee Broad-Specification (ERBS) fuels were supplied by NASA. These fuels were stored in bulk storage tanks. No fuel was added to these tanks during the test program. The Jet-A fuel was commercial Jet-A available at the General Electric plant. Fuel hydrogen content and specific gravity were tracked throughout the test program by analyzing samples of each fuel used during each test run.

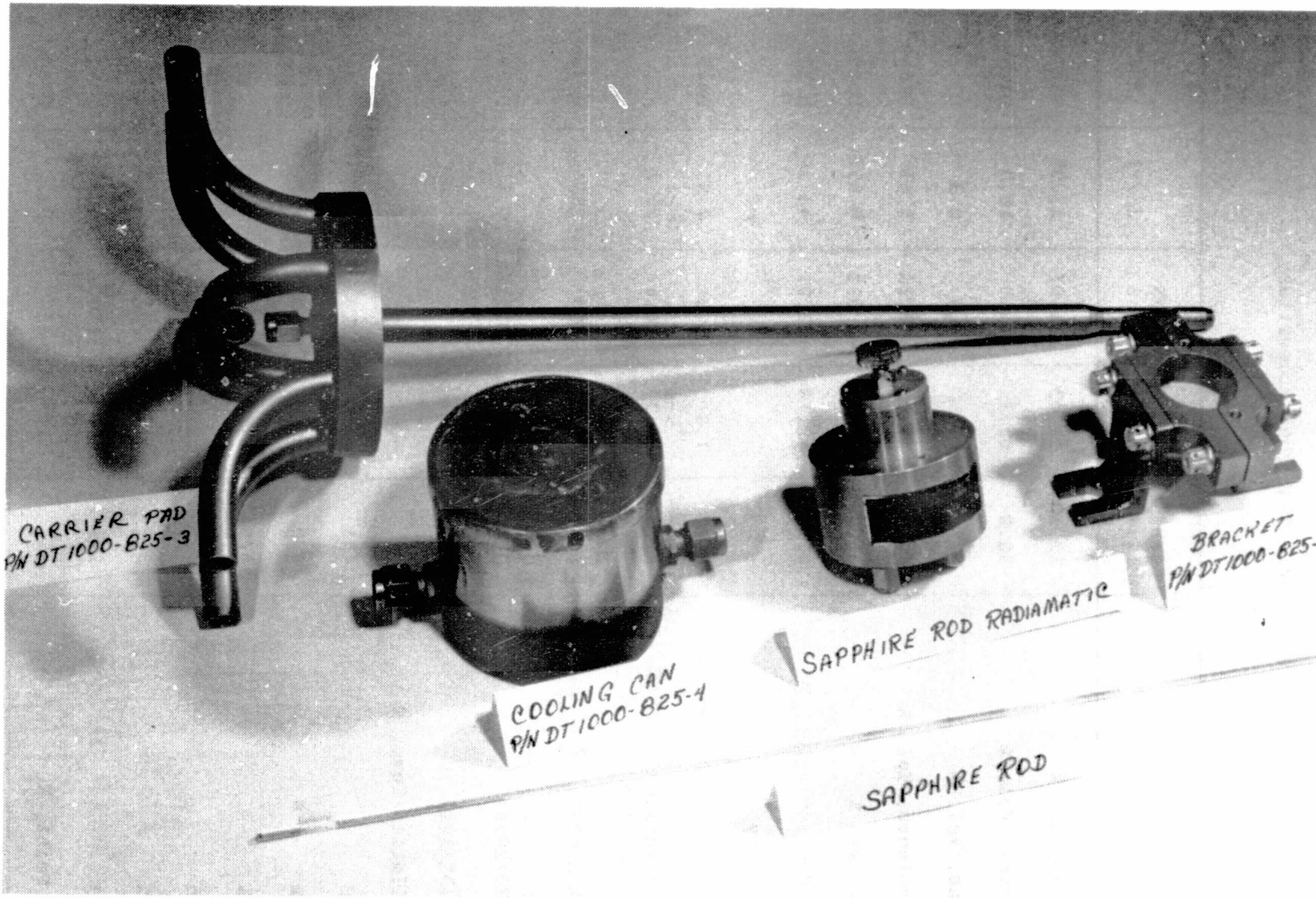

Figure 5-9. Combustor Flame Radiation Measurement Instrumentation Components.

Table 5-2. Test Fuel Properties.

Property Composition	ERBS 12.8	ERBS 12.3	ERBS 11.8	JET-A	METHOD
Hydrogen, WT. %	13.10	12.43	11.97	13.99	E50TF77-51[a]
Aromatics, Vol. %	30.0	42.3	49.9	19.0	D1319
Olefins, Vol. %	0.8	0.8	0.6	0.8	D1319
Naphthalenes, Vol. %	11.05	14.06	16.20	1.61	D1840[b]
Sulfur, Wt. %	0.047	0.040	0.062	0.057	D129
Lower Heating Value, MJ/kg	42.53	42.19	41.91	43.36	D2382
Fluidity					
Viscosity at 250K, mm^2/s	8.8	7.9	7.0	7.3	D445
Surface Tension at 294K, dynes/cm	27.7	28.3	28.6	26.7	
Freezing Point, K	250	248	250	233	D2386
Specific/Gravity (289/289K)	0.8403	0.8525	0.8628	0.8115	D1298
Volatility					
Distillation Temp, K					
IBP	456	440	419	453	
10%	470	459	446	473	
20%	475	472	471	480	
50%	495	502	499	494	
90%	563	566	563	521	
FBP	606	600	600	549	
Flash Point, K	334	326	317	327	D93

a) General Electric macrocombustion method
b) ERBS fuels were diluted with iso-octane to reduce initial Naphthalene content to less than 5% as required by D1840.

As shown in Figure 5-10, measured fuel properties were consistent throughout the test program.

The primary fuel variable for this program was hydrogen content. Fuel physical properties (fluidity and volatility) were not widely varied. The baseline fuel for combustor design and evaluation was the ERBS 12.8. This fuel, which was defined at the Jet Aircraft Hydrocarbon Fuels Technology Workshop held at the NASA-Lewis Research Center in 1977 (Reference 9) has been proposed for the development of future combustors and is intended to be typical of future broadened-properties fuels. The other two ERBS fuels were blended for NASA to meet specific requirements for hydrogen, naphthale, and aromatic contents, as well as flashpoint. NASA analyses of these ERBS fuels are reported in Reference 13. (They are identified as ERBS-3.) Jet-A was required to meet the current specification (D1655).

Although variables other than hydrogen content were not varied systematically, there was some variation from fuel to fuel. Several of the fuel chemical properties are shown as a function of fuel hydrogen content in Figure 5-11. These properties are consistent among the four fuels, with aromatics and naphtalenes both decreasing with increasing fuel hydrogen content. It should be noted, however, that the ratio of aromatics to naphthalenes was much higher in the Jet-A (about 12 to 1) than in the ERBS fuels (about 3 to 1). Hydrogen to carbon atom ratio (n) and stoichiometric fuel/air ratio (f_{st}) are calculated from fuel hydrogen content (H) by the relationships:

$$n = \frac{11.915\ H}{100 - H}$$

and

$$f_{st} = \frac{0.0072324\ (1.008n + 12.01)}{(1 + 0.25n)}$$

which assumes that the air is 20.9495 volume-percent oxygen and that the air has a molecular weight of 28.9666. Lower heating value of the fuel increased

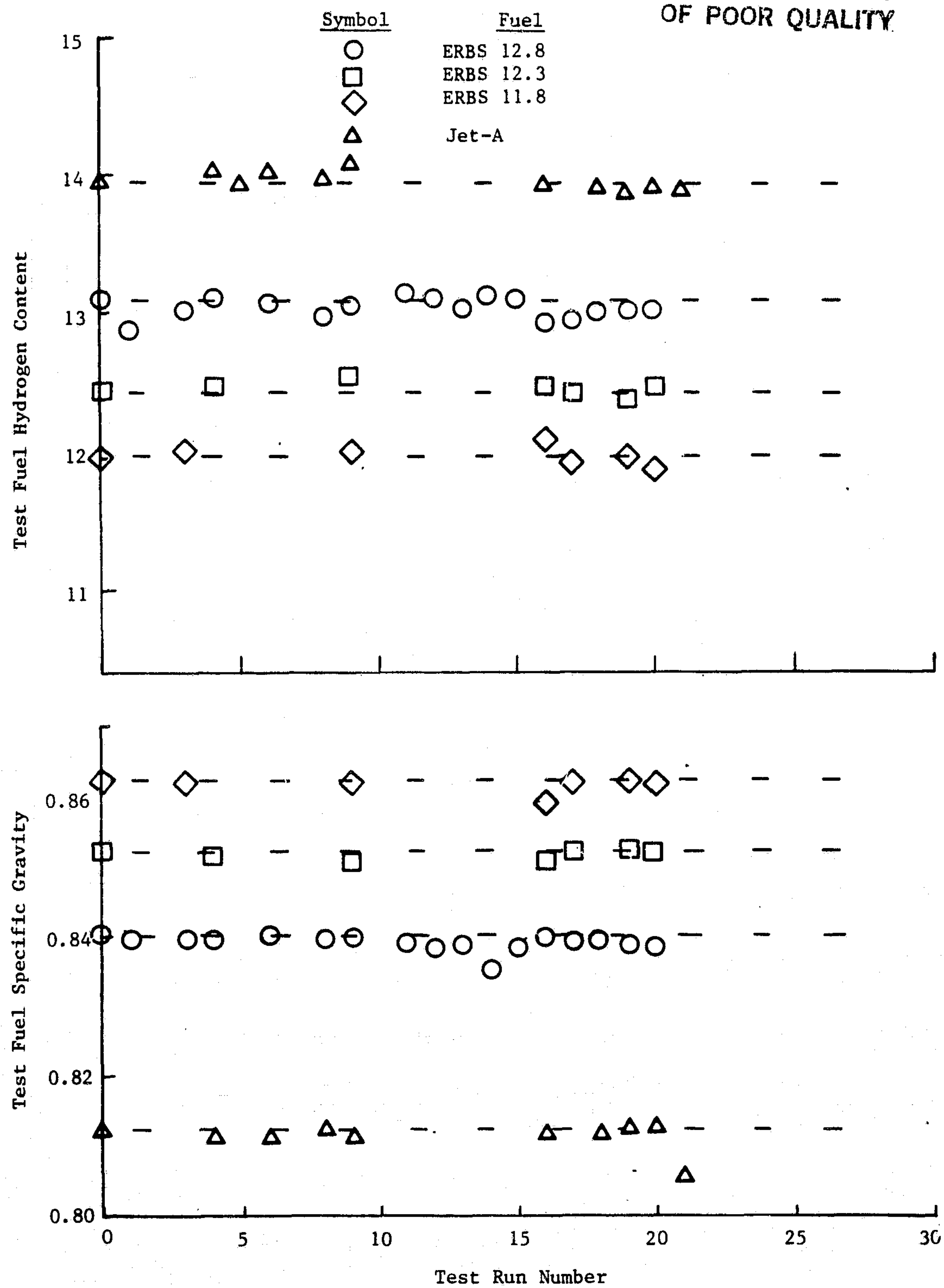

Figure 5-10. Fuel Sample Properties.

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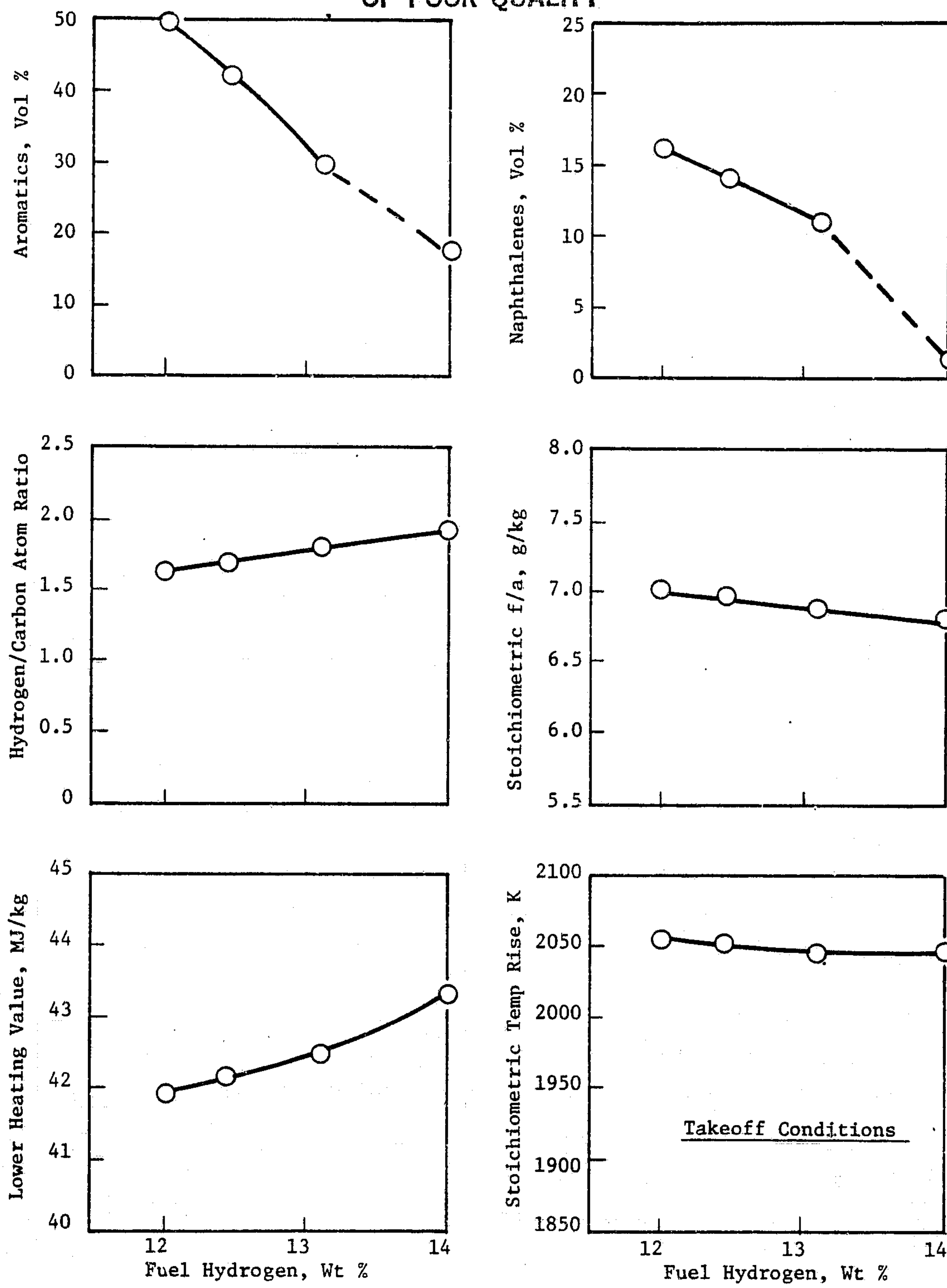

Figure 5-11. Variation in Fuel Chemical and Combustion Properties with Fuel Hydrogen Content.

with increasing fuel hydrogen content, but the stoichiometric flame temperature was virtually the same for all fuels.

Physical fuel properties, shown in Figure 5-12, were not as well ordered as chemical properties. Specific gravity and surface tension both decreased with increasing fuel hydrogen content, consistent with generally observed fuel property trends. ERBS 12.8 was more viscous than Jet-A, as would be expected; however, viscosity among the ERBS fuels tended to increase with increasing hydrogen. This occurred because the lower hydrogen content ERBS fuels were made by mixing ERBS 12.8 fuel with a blending stock which had a low viscosity. This caused the viscosity of the ERBS blends to increase with increasing hydrogen content instead of decreasing as would be expected with lower quality fuels. Relative fuel spray droplet size, which has been used in References 2, 3, and 4 to analyze low power emissions and relight performance, was nearly the same for all three ERBS fuels, and was 6% to 7% higher than that of Jet-A. This parameter was calculated for pressure-atomizing fuel nozzles using the relationship from Reference 14 to estimate the relative fuel spray droplet Sauter Mean Diameter (SMD) from the test fuel density (ρ), surface tension (σ), and kinematic viscosity (ν);

$$\frac{(SMD)}{(SMD)_{Jet-A}} = \left(\frac{\nu}{\nu_{Jet-A}}\right)^{0.16} \left(\frac{\sigma}{\sigma_{Jet-A}}\right)^{0.6} \left(\frac{\rho}{\rho_{JP-4}}\right)^{0.43}$$

The 6% to 7% increase compares to an increase of about 20% for diesel fuel or a decrease of about 20% for JP-4 fuel. The 10% recovery temperature increased slightly with fuel hydrogen content, while the 90% recovery temperature was about 40 K higher for the ERBS fuels than for Jet-A. Overall, the effects of the measured variation in fuel physical properties would be expected to be small. Based on the advanced annular combustor fuel effects correlated in Reference 3, the 7% increase in rela- tive drop size would tend to increase idle coemissions by about 6%. The effect would be almost totally offset by the 27 K decrease in 10% recovery temperature with the lowest hydrogen content fuel.

In summary, the test fuels provide a rather wide range of chemical properties, which are primarily expected to affect high power emissions and

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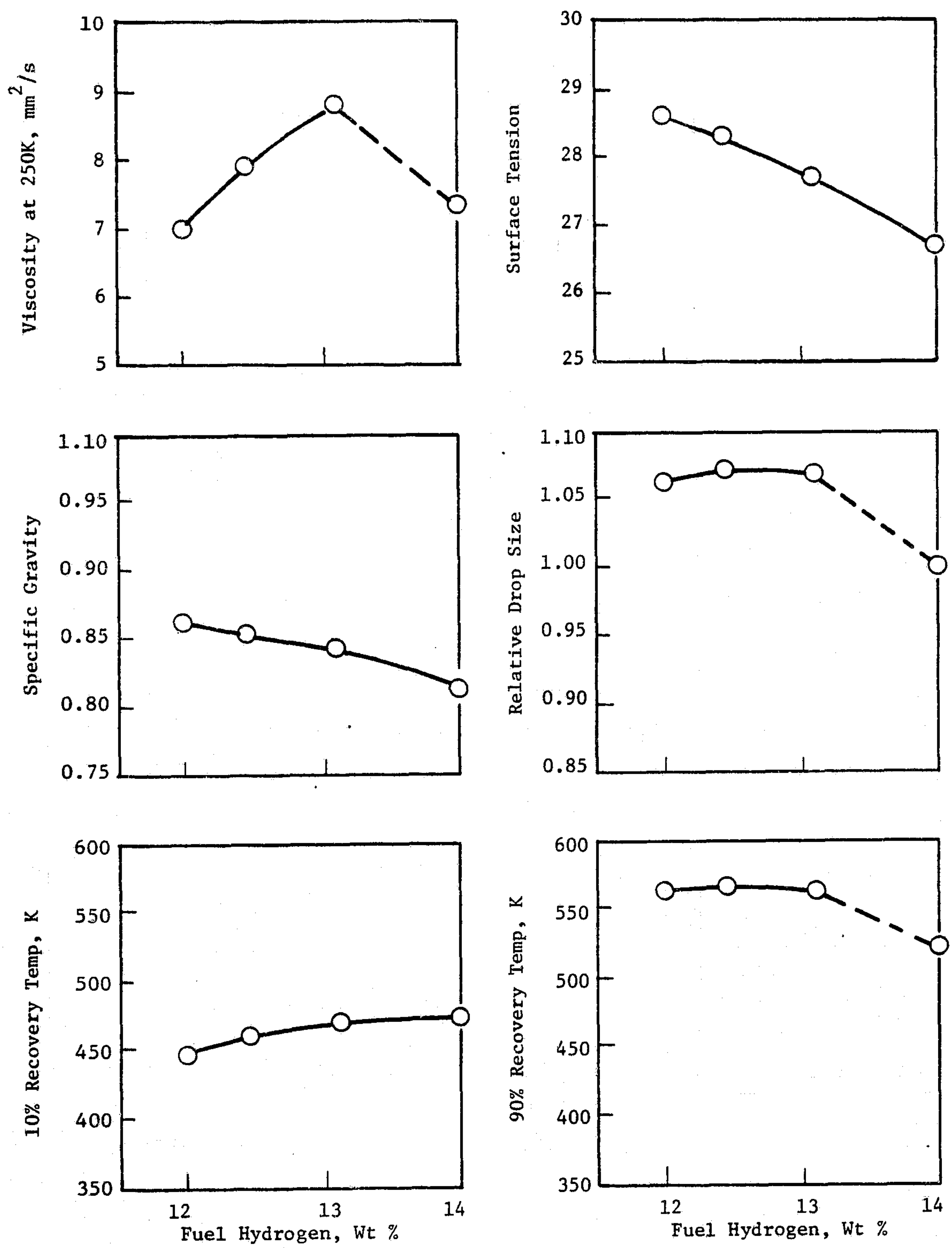

Figure 5-12. Variation in Fuel Chemical and Combustion Properties with Fuel Hydrogen Content.

performance, with a relatively narrow range of physical properties, which are expected to affect low power operation.

5.4 TEST PROCEDURES

The overall test program consisted of a total of 27 test runs to evaluate the 25 different combustor configurations described in Section 4.0. All combustion tests were conducted in the high pressure five-cup sector test rig described above. The test program was divided into two parts. In the initial tests, a baseline configuration of each combustor concept was first tested to evaluate its emissions and performance characteristics and to identify effects of changes in fuel properties. Based on these results, a short series of design modifications and retests was conducted to improve aspects of combustor performance which did not meet the program goals. A total of eight single-annular combustor configurations and six configurations each of the double-annular and variable-geometry combustors were tested in these initial tests. Following the initial tests of all concepts, the two most promising concepts were selected for additional tests to further improve and document combustor emissions and performance characteristics and to document more completely the effects of broadened fuel properties on these characteristics. Two configurations of the single-annular and three configurations of the variable-geometry combustors were evaluated in these final tests.

The original test plan called for evaluation of all combustor configurations with ERBS 12.8 fuel over the abbreviated test point schedule shown in Table 5-3. Selected configurations, including the baseline and most promising configuration of each concept in initial tests and the final test configurations, were to be evaluated over the extended test point schedule using all four test fuels. In the actual test program, which is summarized in Table 5-4, tests were occasionally shortened due to combustor operating limitations, such as relight difficulties with Configuration D-1 and fuel flow limitations with Configurations D-4, V-6, and V-7; problems with the test facility or combustor hardware, as with Configurations S-8, S-9, and V-4; or facility scheduling problems, as with S-1 and S-6. In cases where tests were shortened, additional data were obtained as required in later tests.

Table 5-3. Test Point Schedule.

Abbreviated Schedule				
Condition	Fuel			
	Jet A	ERBS	ERBS 12.3	ERBS 11.8
Taxi-Idle		X		
Approach		X		
Climbout		X		
Takeoff		X		
Cruise		X		
Lean Blowout		X		

Extended Test Point Schedule				
Condition	Fuel			
	Jet A	ERBS	ERBS 12.3	ERBS 11.8
Taxi-Idle	X	X	X	X
Approach	X	X		
Climbout	X	X		
Takeoff	X	X	X	X
Cruise	X	X	X	X
Lean Blowout	X	X		X
Altitude Relight and SLS Ign.*	X	X		X

Note: Parametric changes in fuel viscosity, combustor reference velocity, fuel/air ratio, and fuel or variable geometry scheduling will be conducted at selected operating conditions.

*In low pressure sector

Table 5-4. Sector Combustor Test Summary.

CONFIGURATION	TEST RUN(S)	TESTS CONDUCTED: Steady State Idle	Steady State Approach	Steady State Climb	Steady State Takeoff	Steady State Cruise	Blowout Idle	Blowout Altitude	ERBS 12.8	ERBS 12.3	ERBS 11.8	Jet-A	T/O Press.	Reduced Rull	Data Acquisition Hrs.	Data Acquisition Rdgs.[b]	Test Limitations
Single Annular																	
S-1	2,3	X	X	X	X	X	X		X			X	X		21.7	15	Facility Schedule
S-2	3			X	X				X				X		2	2	↓
S-3	4	X	X	X	X	X	X		X				X		9.3	11	None
S-4	5	X	X	X	X	X	X		X	X		X	X		13.8	18	↓
S-5	6	X	X	X	X	X	X		X				X	X	12.8	10	↓
S-6	7			X	X	X						X	X	X	8.4	7	Facility Schedule
S-7	8	X	X	X	X	X	X		X			X	X		8.8	10	None
S-8	11	X	X	X	X	X	X		X				X		7.7	6	Swirler Failure
S-9 [a]	21,22	X	X	X	X	X	X	X	X		X	X		X	11.5	11	↓
S-10 [a]	25,26	X	X	X	X	X	X		X	X	X	X		X	16.7	19	None
Double Annular																	
D-1	1	X	X	X	X	X			X			X	X		17.6	16	Lightoff Difficulty
D-2	9	X	X	X	X	X	X		X	X	X	X	X		22.7	21	None
D-3	14	X	X	X	X	X	X		X				X		9.5	11	↓
D-4	15	X	X			X	X		X						5.5	9	Fuel Nozzle Flow Limits
D-5	16	X	X	X	X	X	X		X	X	X	X	X		12.3	14	None
D-6	17	X	X	X	X	X	X		X	X	X	X		X	15.4	15	↓
Variable Geometry																	
V-1	10	X	X	X	X	X	X		X	X	X	X	X		22.8	18	None
V-2	12	X	X	X	X	X			X				X		11.3	10	↓
V-3	13	X	X	X	X	X			X				X		8.4	9	↓
V-4	18	X	X	X		X			X						6.2	8	Facility Problem
V-5	19	X	X	X	X	X			X	X	X	X	X		17.6	24	None
V-6	20	X							X	X	X	X			4.3	12	Fuel Nozzle Flow Limits
V-7 [a]	23	X	X				X	X	X	X	X	X			6.8	13	↓
V-8 [a]	24		X	X	X	X			X	X	X	X		X	13.0	15	None
V-9	27		X	X	X	X			X	X	X	X		X	4.0	4	↓

Notes: a - Final Test Configuration
b - Does not Include Relight/Blowout

Combustor inlet conditions used for the steady state five-cup sector tests are shown in Table 5-5. These test conditions were scaled from the CF6-80A cycle conditions presented in Table 5-1. Compressor discharge bleed flow levels identical to those used for turbine cooling in the engine were withdrawn at all operating conditions. Combustor sidewall cooling equivalent to 5% of sector combustor airflow was also supplied at all operating conditions. Two possible pressure levels are presented for the climb and takeoff conditions in Table 5-5. One is the actual pressure level obtained in the engine, while the other is equivalent to 60% of the full rated value. For the reduced pressure points, fuel and air flows were also reduced to 60% of the full pressure value to maintain the proper Mach numbers, velocities, and fuel/air ratios within the combustor system. The reduced pressure points were used in a majority of the test runs to conserve fuel and the electrical power needed to drive the air supply system, and to avoid the additional facility preparation that was required to run at full rated pressure. At least one configuration of each concept was evaluated with all four test fuels at the full rated pressure. Two of the single-annular configurations were also operated over a range of pressures to evaluate pressure effects on combustor emissions and performance. Gaseous emission data were corrected for small deviations from the test point pressure, inlet temperature, and reference velocity; and reduced pressure test points were corrected to true engine pressure, by using the basic corrections described in Reference 10. These corrections were as follows:

$$(EINO_x)_2 = (EINO_x)_1 \; (P_2/P_1)^{0.37} \; (V_{r1}/V_{r2})$$

$$* \exp \; (T_2 - T_1)/195.6 \; + \; (H_1 - H_2)/53.19$$

$$(EIHC)_2 = (EICH)_1) \; (P_1/P_2) \; (V_{r2}/V_{r1})$$

$$* \exp \; (T_1 - T_2)/58.9$$

$$(EICO)_2 = (EICO)_1 \; (P_1/P_2)^n \; (V_{r2}/V_{r1})$$

$$* \exp \; (T_1 - T_2)/82.8$$

C-2

Table 5-5. Combustor Inlet Conditions (CF80 Cycle) for Five-Cup Sector Combustor Rig Tests.

	Combustor Airflow W_c, kg/s	Inlet Total Pressure PT_3, MPa	Inlet Total Temperature T_3, K	Reference Velocity V_R, m/s	Fuel Flow W_f, g/s	Fuel/Air Ratio f_m, g/kg
Taxi-Idle	2.18	0.301	431	15.8	23.3[a]	10.7
Approach	7.08	1.102	614	20.0	93.9	13.2
Climbout (Reduced P_3)	8.05	1.456	772	21.6	169.6	21.1
Takeoff (Reduced P_3)	9.01	1.673	805	21.9	205.9	22.8
Climbout (Full P_3)	13.42	2.426	772	21.6	282.6	21.1
Takeoff (Full P_3)	15.02	2.789	805	21.9	343.1	22.8
Normal Cruise	5.49	0.936	686	20.4	100.8	18.3

a - Fuel flow is increased by 50% for single-annular combustor fuel staging simulation.

where The Subscript 2 indicates a corrected or nominal value

The Subscript 1 indicates a measured (test) value

$EINO_x$ is the nitrogen oxides emission index

EIHC is the unburned hydrocarbons emission index

EIHO is the carbon monoxide emission index

H is absolute humidity (g/Kg)

P is pressure

T is temperature (K)

V_r is reference velocity

$n = 0.2 \quad 100/(EICO)_1{}^{0.7} \leq 2.0$

The NO_x pressure correction exponent was reduced slightly from the value given in Reference 10, based on later results reported in References 15 and 16. Both the pressure and humidity factors for NO_x have previously been shown to be applicable to either single- or double-annular combustor designs. NO_x emissions were corrected to 6.29 gH_2O/kg dry air, the "reference-day condition" defined by the U.S. Environmental Protection Agency. These NO_x corrections were significant, particularly on the reduced pressure, simulated climb, and takeoff test points. For data obtained at 60% pressure, the corrected NO_x values were 20.8% above the measured levels, based on the pressure correction alone. Due to condensation removal in the air supply system interstage coolers, combustor inlet air humidity levels for rig tests were normally between 1 and 2 gH_2O/kg of dry air. Corrected NO_x values throughout the power range were therefore reduced by 8% to 10% relative to the measured value as a result of the humidity correction. Inlet temperature and reference velocity were set very close to the actual engine values at all operating conditions, so corrections for these conditions were small.

CO and HC corrections were also small. AT the low and intermediate power conditions, actual engine inlet conditions were set. When the 60% pressure climb and takeoff operating conditions were used, the corrected values for CO were up to 64% below measured values. However, measured CO and HC levels were normally very low at these conditions, so even this large percentage correction was not very significant to overall emissions or performance.

In this report, emission levels corrected to the reference engine operating conditions have been used in most data presentations. When used, uncorrected levels have been identified as "measured" values.

The gaseous emission goals of this program have been stated in terms of "EPA Parameters" (EPAPS) specified by the U.S. Environmental Protection Agency (Reference 8). These EPAPS represent a maximum allowable quantity of emission for a prescribed takeoff landing cycle (in grams) normalized by rated thrust (in kN). This can be expressed as:

$$EPAP_i = \frac{j\ (60t_j)\ (W_{f_j})\ (EI_{ij})}{F_r}$$

where

EI = Corrected emission index (g/kg fuel)

$EPAP$ = Emission Parameter (g/kN)

F_r = Rated thrust (kN)

t = Prescribed time (minutes)

W_f = Fuel Flow rate (kg/s)

and the subscripts are:

i = Type of emission (CO, HC, NO_x)

j = Prescribed power level (idle, approach, climbout, and takeoff).

For a Class T2 engine such as the CF6-80A, the prescribed times are 26.0, 4.0, 2.2, and 0.7 minutes at idle, approach, climb, and takeoff, respectively. As shown in Table 5-6, most of the CO and HC EPAPS are normally due to idle emissions, with a significant contribution from approach. Climb and takeoff contributions are relatively small. About half of the NO_x EPAP comes from emissions at climb power, with the remainder coming primarily from approach and takeoff.

Table 5-6. Contribution of the Various Operating Condition to EPA Parameters.

Emission	Percent Contribution To Total EPA Parameter*			
	Idle	Approach	Climb	Takeoff
Carbon Monoxide				
Single Annular	76	10	9	5
Double Annular	86	11	2	1
Variable Geometry	77	8	11	4
Hydrocarbons				
Single Annular	42	55	2	1
Double Annular	52	29	14	5
Variable Geometry	96	1	2	1
Oxides of Nitrogen				
Single Annular	6	12	57	25
Double Annular	8	22	47	25
Variable Geometry	6	27	53	26

* For final test configuration of each concept, burning ERBS 12.8 fuel.

Smoke levels have been reported "as measured" at the combuster exit. In an actual engine application, smoke levels would be reduced by the dilution effect of turbine cooling air. The effect of cooling air dilution, based on the relationship between smoke number and carbon particle concentration reported in Reference 17, is shown in Figure 5-13. In order to meet the engine smoke number requirement of 19.2, the combustor smoke number must be below 23.

Low power fuel staging in the single-annular combustor was simulated in the sector combustor with uniform fueling at an increased fuel/air ratio. Fuel flow was increased to provide the same flow to each injector as would be provided to the fueled injections in the engine. For example, to simulate a fuel staging scheme where two-thirds of the nozzles were fueled (such as the 4/2 staging configuration), flow to each of the five test combustor injectors was increased by 50%. This simplified fuel staging simulation does not accurately account for the unfueled regions where CO and HC can be produced in the engine, and is therefore somewhat optimistic. Comparison with engine test data indicates that CO levels obtained with this simulation are representative, while measured HC levels can be on the order of 50% below actual engine levels.

Except for smoke, all of the data were processed on-line by a time-sharing computer system. Smoke spots were interpreted following the run. For a data reading, steady-state operation was established at the desired test conditions, and gas sample flow was routed to the emissions analyzers. After the emission analyzers had stabilized, the facility digital data acquisition system was activated to input all operating data into the time-share system.

A measure of combustor relight/lean blowout limits was obtained for each combustor configuration by measuring lean blowout at the idle operating condition. Steady-state operation was first established at the idle condition. Fuel flow was then reduced until blowout occurred, as indicated by a rapid decrease in combustor liner temperature.

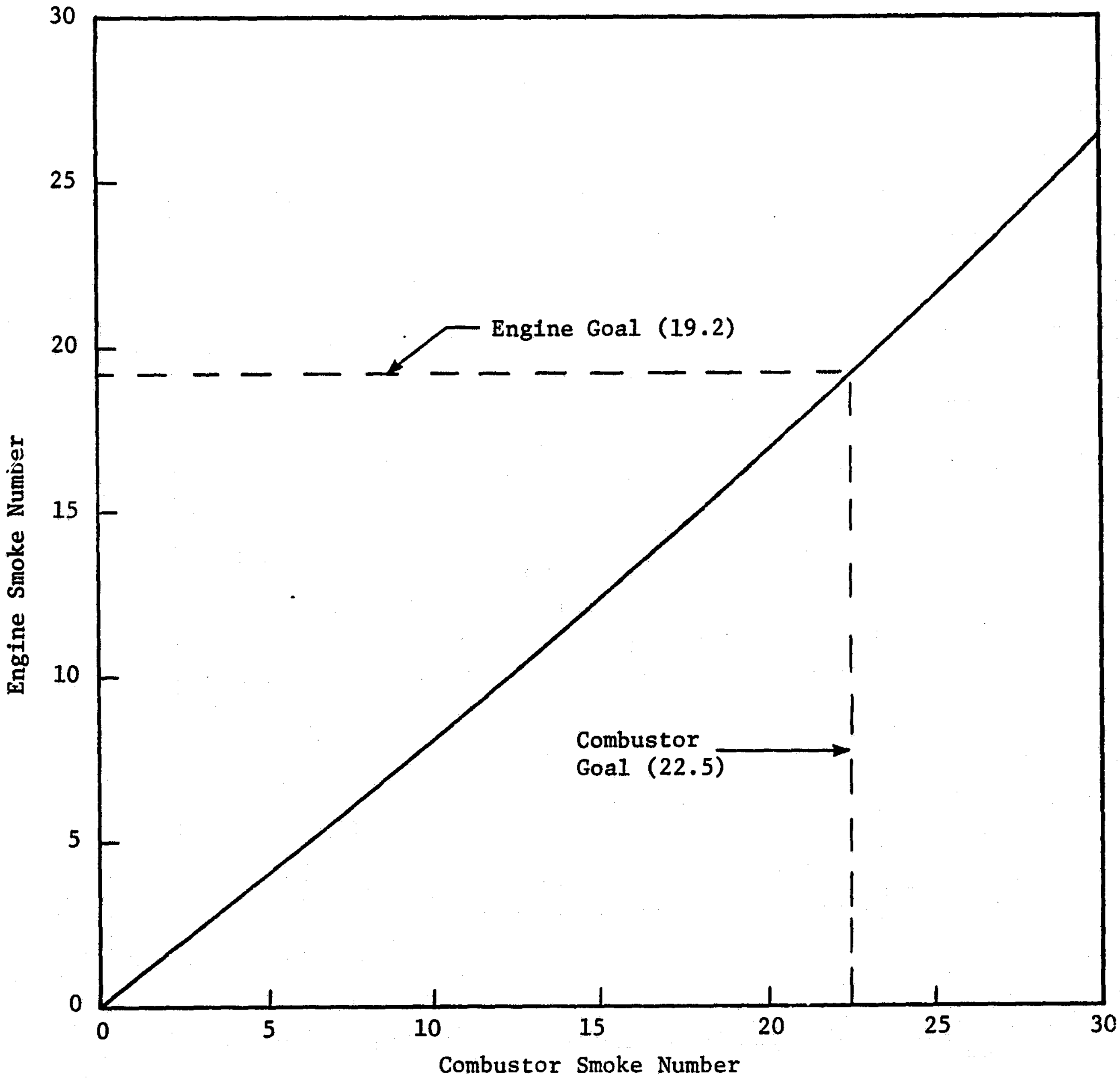

Figure 5-13. Relationship Between Combustor and Engine Smoke Levels.

Attitude relight/pressure blowout tests at subatmospheric pressures were also conducted during the final tests of the two most promising concepts.

The sector combustor test rig used a torch ignitor for light off, rather than the spark type ignitor normally used in the engine and in full-annular tests. Therefore, ignition results were not directly comparable with full-annular tests. In order to obtain a direct comparison with annular results, pressure blowout was also measured. Tests were conducted by first attempting relight at one of four different airflow/pressure test conditions corresponding to the relight goal at four different flight Mach numbers (Table 5-7). All tests were conducted with ambient fuel and air inlet temperatures and with minimum fuel flow (69 g/s is the minimum fuel flow that the engine control will meter). In cases where ignition was not obtained, pressure was raised until light off occurred. Early in the test series, it was found that the hydrogen torch would not light reliably below a pressure of about 55 kPa, so pressures above this level were used for all ignition. After steady-state operation was established, pressure was reduced until operation became somewhat unsteady or until the pressure goal for a particular airflow level was reached, at which point a data reading was obtained. Pressure was then further reduced until blowout occurred. A second data reading was obtained after blowout.

Table 5-7. Altitude Relight Test Points

Altitude km	Mach Number	Combustor Reference Pressure kpa	Combustor Reference Velocity, m/s	Combustor Fuel/Air Ratio g/kg
9.00	0.54	34.5	9.7	51.0
9.14	0.70	39.3	14.2	30.5
9.14	0.83	48.3	16.2	21.8
9.14	0.95	65.5	18.7	13.9

6.0 TEST RESULTS

During the test program, the performance and emissions characteristics of the single-annular, double-annular, and variable-geometry combustor concepts were improved through an extensive sequence of test modifications and retests. These tests included both full-scale high pressure sector combustor tests and small-scale swirler/fuel injector development tests. Each of the high pressure tests was conducted with the objective of improving one or more performance or emission variable. The intent of each of the specific modifications has been discussed in Section 4.0. The effects of changes in fuel properties, with emphasis on fuel hydrogen content, were documented on at least two configurations of each combustor concept by operating on the different fuels, as described in Section 5.0.

In the following sections, brief summaries of significant test results obtained with each of the combustor concepts are presented. The three sections deal with the single-annular, double-annular, and variable-geometry concepts, respectively. Each section is further divided into subsections describing (1) the general operating characteristics of the subject combustor concept, based on results obtained with the best configuration of that concept; (2) a summary of development progress with the subject concept, including specific effects of the key combustor modifications; and (3) a description of the observed effects of variation of fuel properties on combustor performance and emissions.

The following discussions summarize the more significant results obtained with each combustor concept. Detailed summaries of test data obtained with each of the different combustor configurations are contained in Appendix A.

6.1 SINGLE-ANNULAR COMBUSTOR

6.1.1 General Emissions and Performance Characteristics

The general emissions and performance characteristics of the single-annular combustor concept will be described in a discussion of the results obtained with the two final single-annular combustor configurations (S-9 and S-10). These configurations incorporated all of the best single-annular combustor design features developed during the test program and thus provided the best emissions and performance obtained with this design concept. Configuration S-10 was tested for idle blowout and steady-state performance with all four test fuels. Actual engine pressure levels were used at all conditions except takeoff, where pressure was reduced slightly (by about 8%) due to a temporary facility preheater problem. Since combustor inlet conditions were very close to actual engine conditions, no significant corrections to the test data were required. Although the emissions and performance characteristics of Configuration S-10 were improved relative to those of earlier configurations of this concept, trends in these characteristics at different operating conditions are generally typical of all single-annular combustor configurations. Where characteristics were significantly different for earlier configurations, these specific differences are also discussed. Configuration S-9 was tested at altitude relight conditions on three different fuels.

In this section, the single-annular combustor operating characteristics are presented as a function of combustor inlet temperature. Combustor inlet temperature increases monotonically with power level at sea level operating conditions, and the inlet temperatures for the sea level idle, approach, climb, and takeoff conditions will be shown on these plots of the various operating characteristics. By describing operating conditions in relation to combustor inlet temperature, it becomes convenient to include the cruise characteristics, and the inlet temperature corresponding to normal cruise will also be included. As shown in Figure 6-1, combustor inlet pressure, fuel/air ratio, and reference velocity all increase with inlet temperature at sea level conditions. This figure also shows

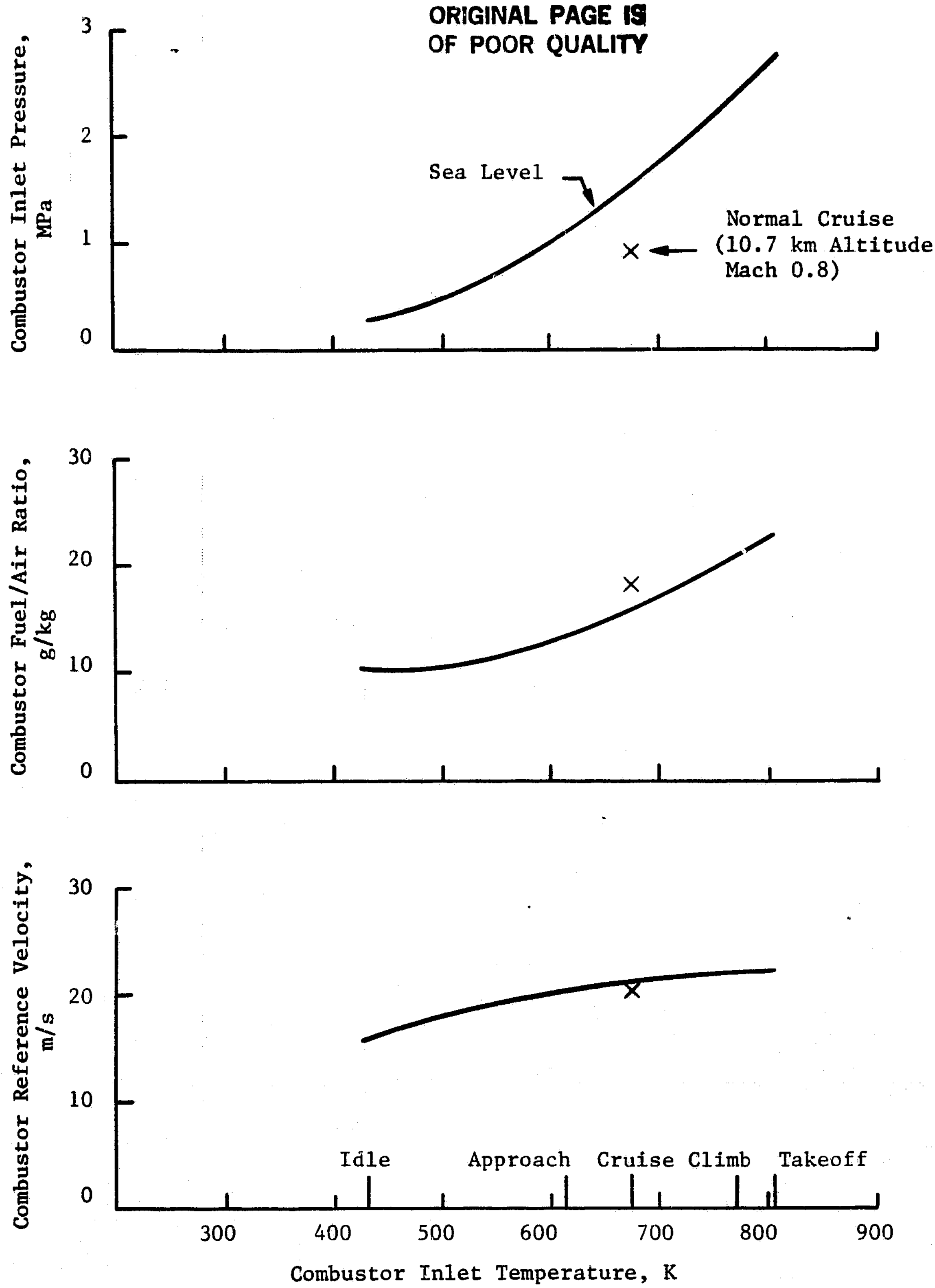

Figure 6-1. Relationship Between Combustor Inlet Temperature and Other Combustor Inlet Conditions.

that cruise pressure falls well below the sea level operating line, while cruise fuel/air ratio and reference velocity are close to the corresponding sea level values.

6.1.1.1 Emissions

Single-annular combustor carbon monoxide and unburned hydrocarbon levels are shown as a function of combustor inlet temperature in Figure 6-2. Both CO and HC levels are highest at the idle condition, dropping very rapidly as power is increased. The hydrocarbon levels obtained at idle with Configuration S-10 were exceptionally low. Idle HC levels for other configurations of this combustor concept were typically an order of magnitude higher than approach HC levels. For the single-annular concept, the contributions of the approach, climb, and takeoff power level to the CO and HC EPA parameters were generally insignificant compared to the idle contribution.

The idle data of Figure 6-2 represent a 4/2 fuel staging configuration in which two-thirds of the fuel nozzles are fueled at idle. As described previously, this staging was simulated in the sector by increasing the overall fuel/air ratio by 50%. The effects of fuel/air ratio on idle CO and HC emissions from two different single-annular combustor configurations are shown in Figure 6-3. Both CO and HC increase rapidly as fuel/air ratio is decreased. Without staging, idle CO levels are approximately tripled, to a level between 50 and 60 g/kg. The effect on HC levels is even stronger.

The calculated CO and HC EPA parameters for Configuration S-10 with 4/2 staging are 19.6 gCO/kN thrust and 0.4 gCH_4/kN thrust, respectively. These levels are well below the program goals of 36.1 gCO/kN thrust and 6.7 gCH_4/kN thrust. Based on idle results obtained with Configuration S-9, CO would increase to about 35.4 g/kN with 5/1 staging (marginally meeting the goal) and without staging would be well above the goal at a level of about 67 g/kN. Unburned hydrocarbons would increase to a level slightly above the goal, at 9.4 g/kN with 5/1 staging and would again be well above the goal at about 28 g/kN without staging.

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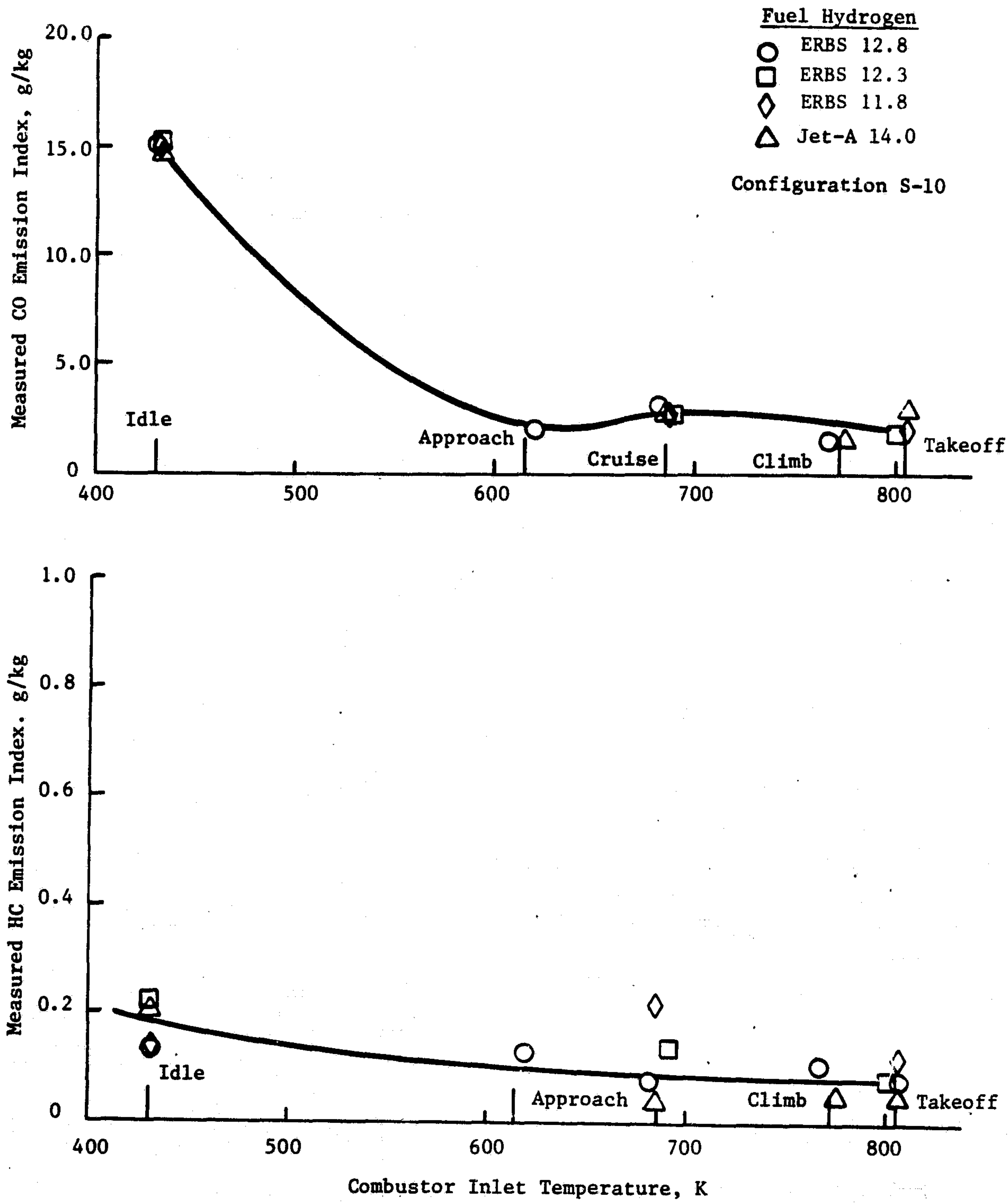

Figure 6-2. Single-Annular Combustor CO and HC Emissions.

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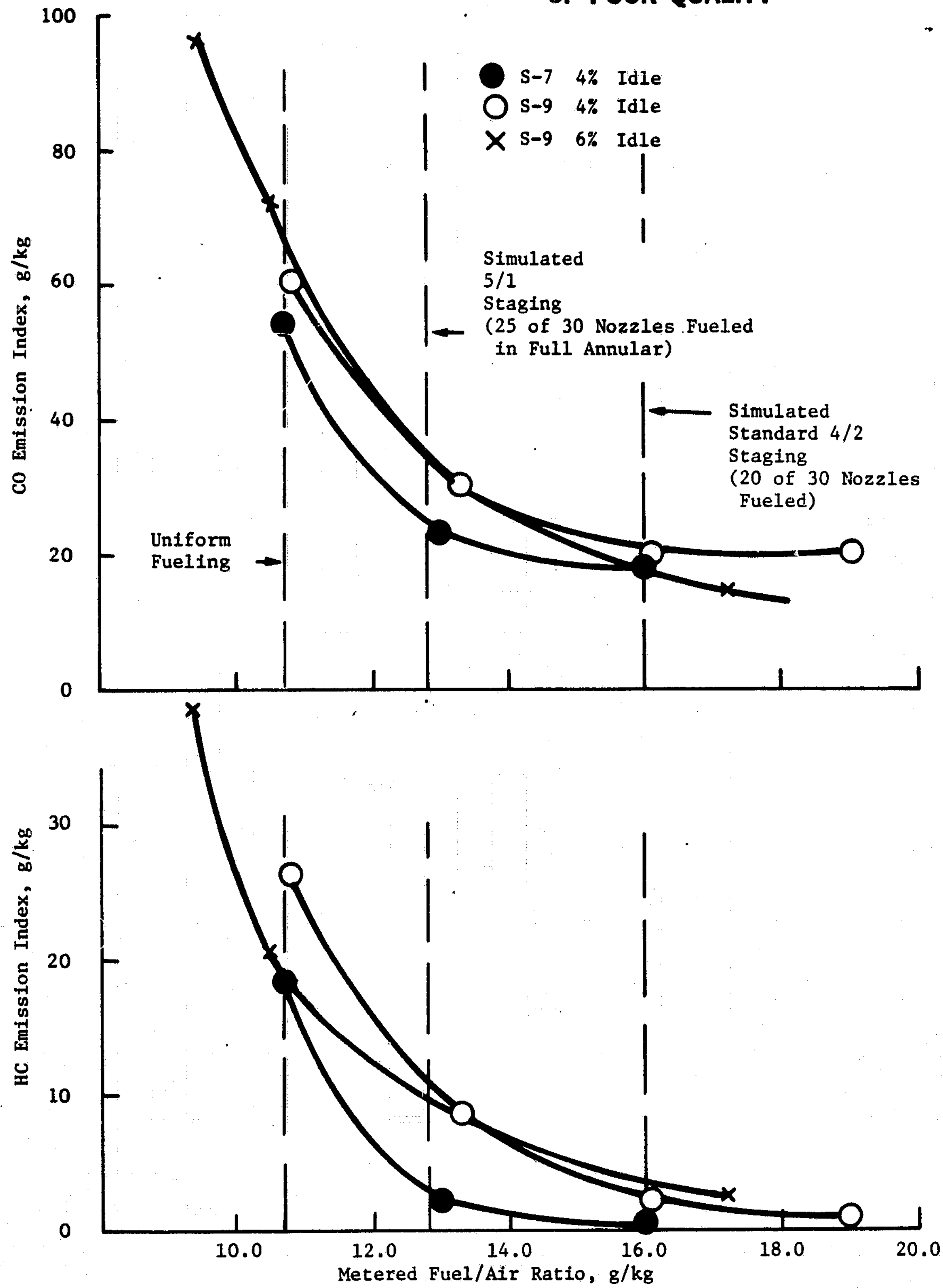

Figure 6-3. Effect of Fuel Staging on Single-Annular Combustor Emissions.

NO_x and smoke emission levels over the combustor operating range are shown in Figure 6-4. NO_x emissions increase rapidly as power level is increased. Note that cruise NO_x levels fall slightly below the sea level values at the same inlet temperature, due to the lower combustor pressure at cruise (Figure 6-1). NO_x levels are highest at takeoff, with slightly lower levels obtained at climb. However, the climb levels account for the major portion of the NO_x EPA parameter because of the long period of time during which the engine is at climb power in the EPA specified cycle. The NO_x EPA parameter for Configuration S-10 was 60.4 gNO_2/kN thrust, about 70% above the program goal of 35.3 g/kN.

Smoke levels are also highest at takeoff conditions, decreasing rapidly as power is reduced to approach power. Going from approach to idle, smoke levels tended to increase in several configurations of this concept due to the higher local fuel/air ratios obtained with fuel staging at idle. In all cases, the highest smoke levels were obtained at takeoff conditions. Since the smoke emissions goal was stated in terms of the maximum smoke number, the ability of a concept to meet the smoke goal depended only on takeoff smoke levels. Smoke levels with Configuration S-10 were safely below the program goal of a smoke number of 23 at the combustor exit.

The effects of variation in combustor fuel/air ratio on NO_x and smoke emissions at takeoff operating conditions are shown in Figure 6-5. As fuel/air ratio is increased, NO_x decreases gradually, and smoke is increased. These characteristics are typical of a conventional combustor having an effective primary zone equivalence ratio above unity (rich primary zone).

6.1.1.2 <u>Performance</u>

The single-annular combustor provided good performance over the combustor operating range. Combustion efficiency levels with Configuration S-10 were 99.6% at idle with fuel staging, and were higher than 99.9% at the approach power level and above, based on gas sample analysis. Average combustor pressure drop, corrected to takeoff conditions, was 4.3%. Both of these values easily meet the program goals.

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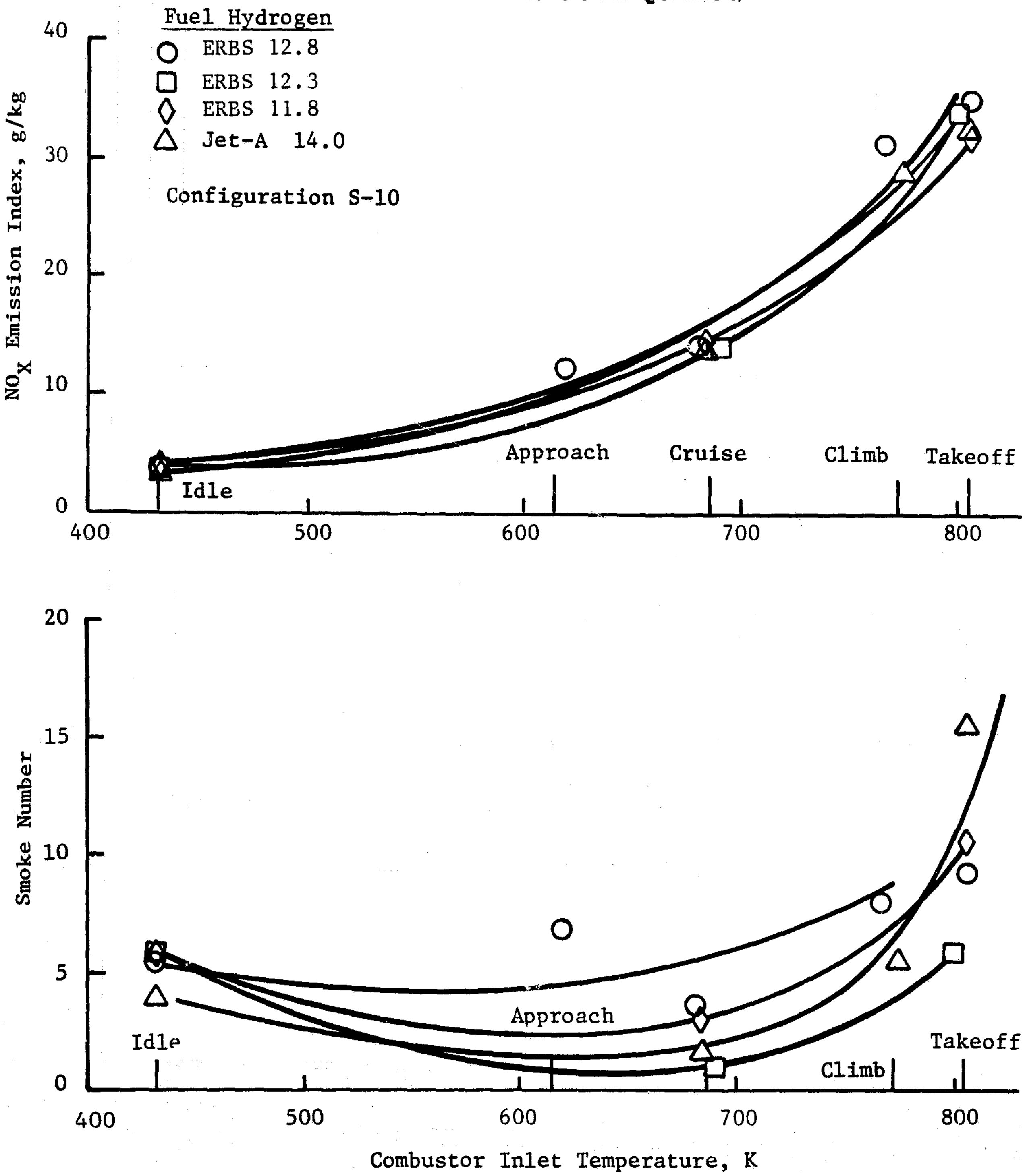

Figure 6-4. Single-Annular Combustor NO_X and Smoke Emissions.

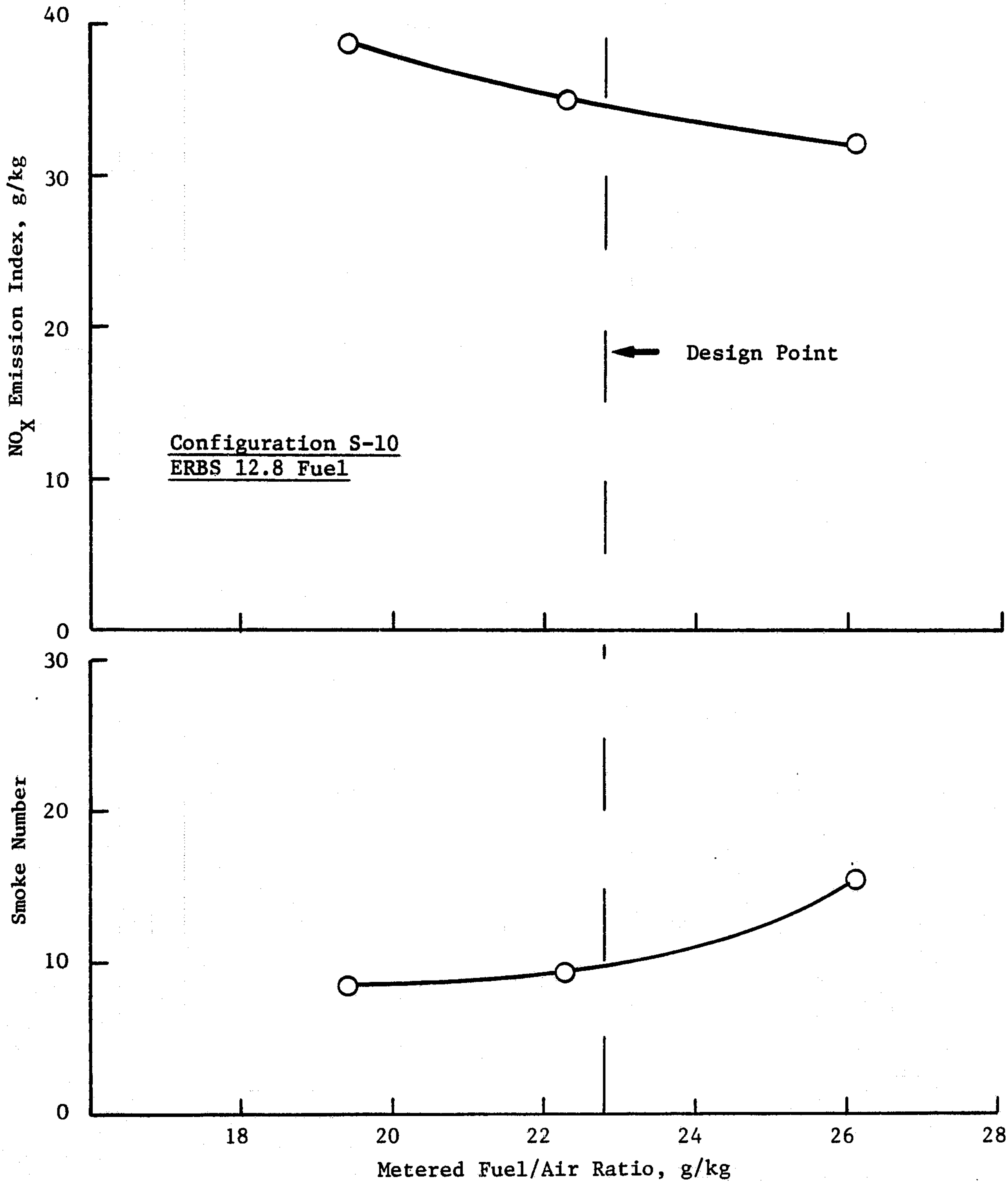

Figure 6-5. Effect of Fuel/Air Ratio on Single-Annular NO_X and Smoke Emissions at Takeoff.

Average and maximum liner temperatures over the combustor operating range are described in Figure 6-6. In this figure, the temperature differential between the liner metal temperatures and the corresponding combustor inlet temperature has been used to describe the liner temperature. This tends to correct for the effects of small variations in inlet temperature. The largest liner temperature differential occurs at the takeoff condition, where combustor fuel/air ratio is at its highest value. Actual liner temperatures are also higher by far at this operating condition since the combustor inlet temperature is also at its highest value at this condition. Liner temperature differential is higher at idle conditions than at approach due to the increased idle fuel/air ratio with fuel staging. In a full-annular combustor, the average liner temperatures would be somewhat lower with fuel staging at idle due to the effect of cold regions of the liner adjacent to unfueled nozzles (which are not simulated in the sector), but the peak temperatures measured in the sector are representative. As shown in Figure 6-7, both average and maximum liner temperatures are approximately proportional to combustor fuel/air ratio over the combustor operating range. This is as expected at lower fuel/air ratios where the combustor primary zone is lean. Under these conditions, internal temperatures throughout the combustor are increased with increasing fuel/air ratios, resulting in higher convective and radiature heat transfer. At higher fuel/air ratios, the curves tend to flatten out as the equivalence ratio in forward regions of the combustor is increased above stoichiometric. When this occurs, bulk temperatures in these regions begin to decrease with increasing fuel/air ratio. However, liner temperatures continue to rise to a lesser extent in these regions due to increased radiation resulting from higher flame emissivity (more smoke formation) and increased reaction at the boundary between the cooling film and the rich primary zone combustion products. Thus at high fuel/air ratios, the forward portions of the combustor are less sensitive to changes in fuel/air ratio than the aft portions. This effect is shown in Figure 6-8, which indicates the percent change in liner temperature differential (liner temperature less combustor inlet temperature) for four

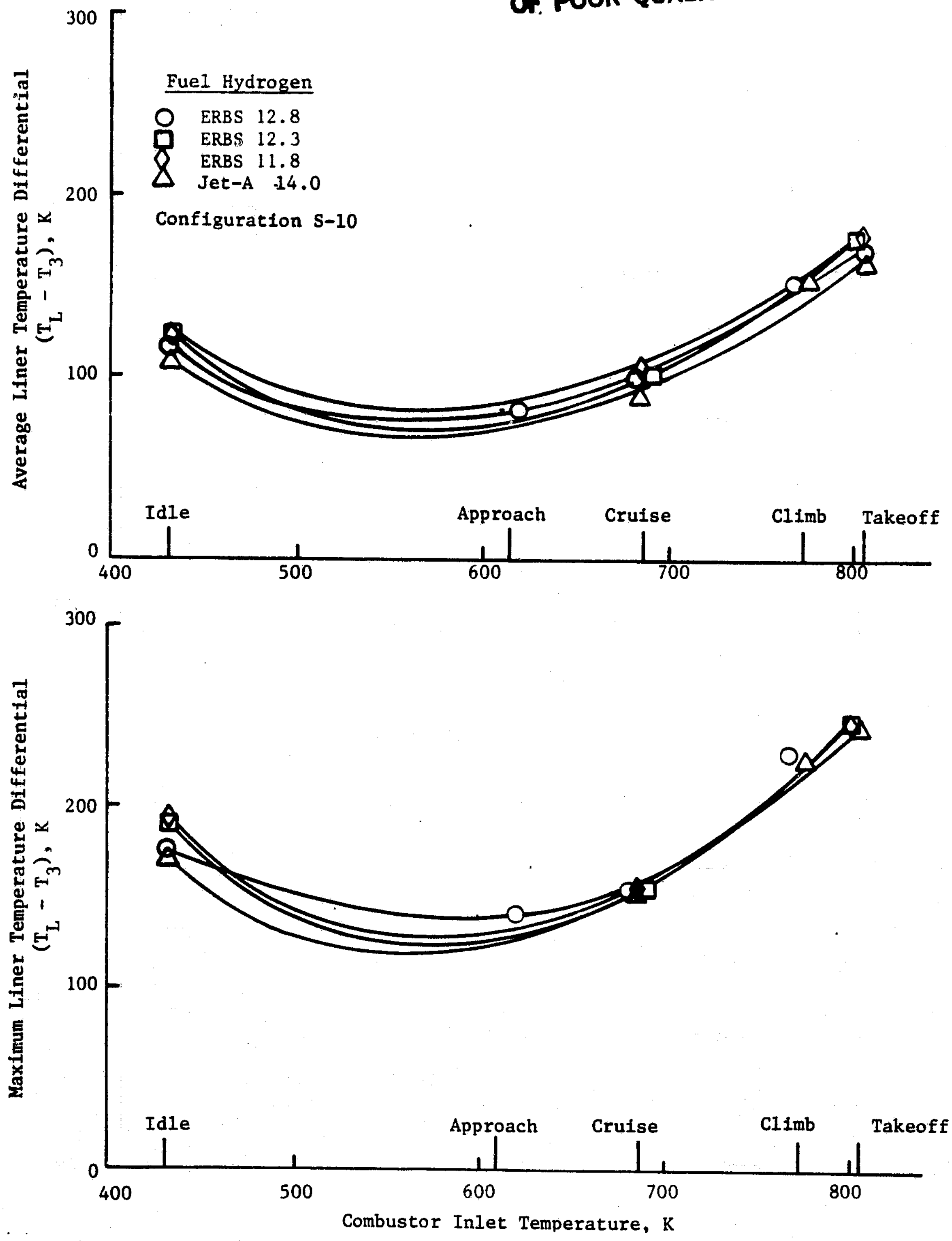

Figure 6-6. Single-Annular Combustor Average and Maximum Liner Temperatures.

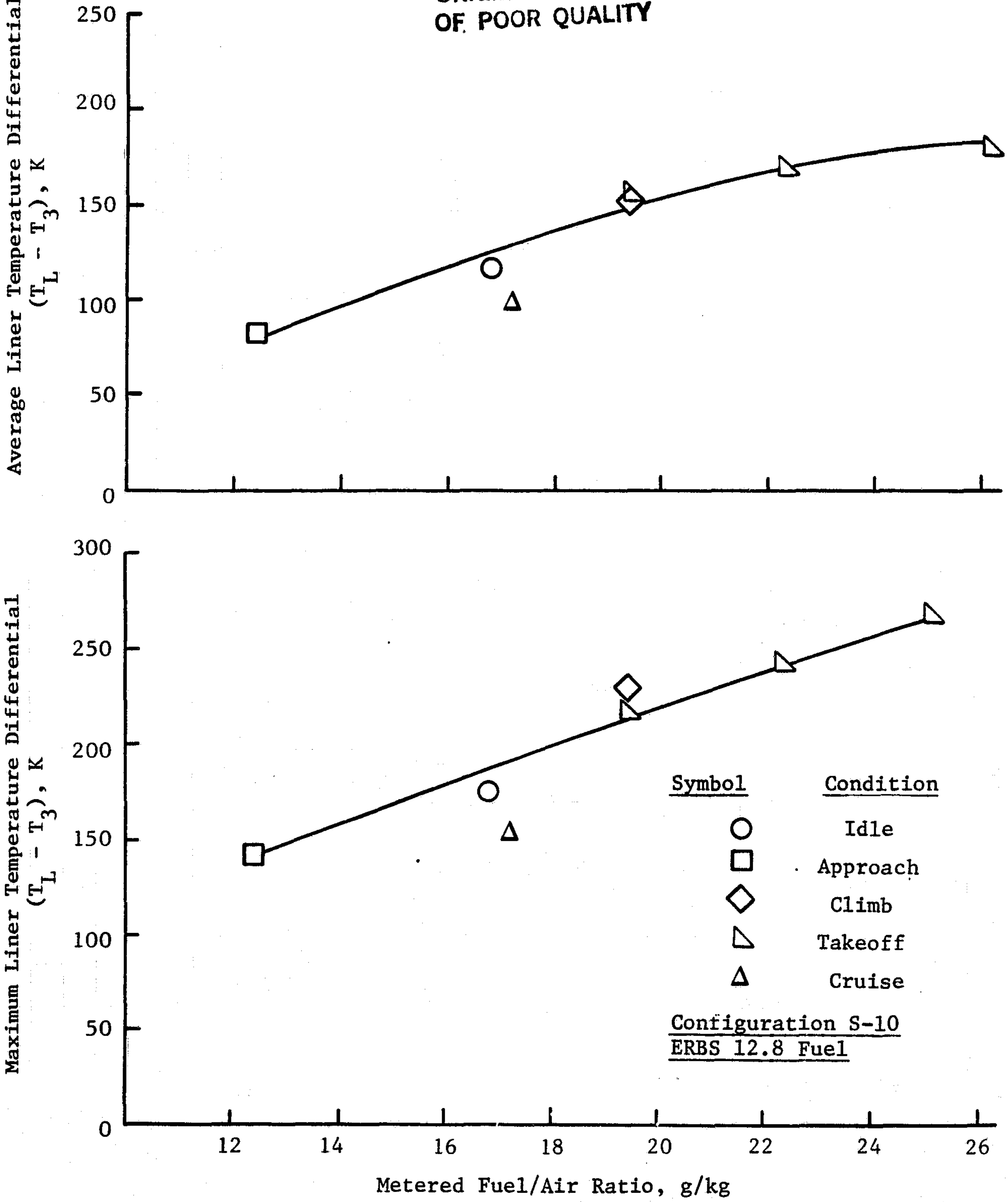

Figure 6-7. Effect of Fuel/Air Ratio on Single-Annular Combustor Liner Temperature.

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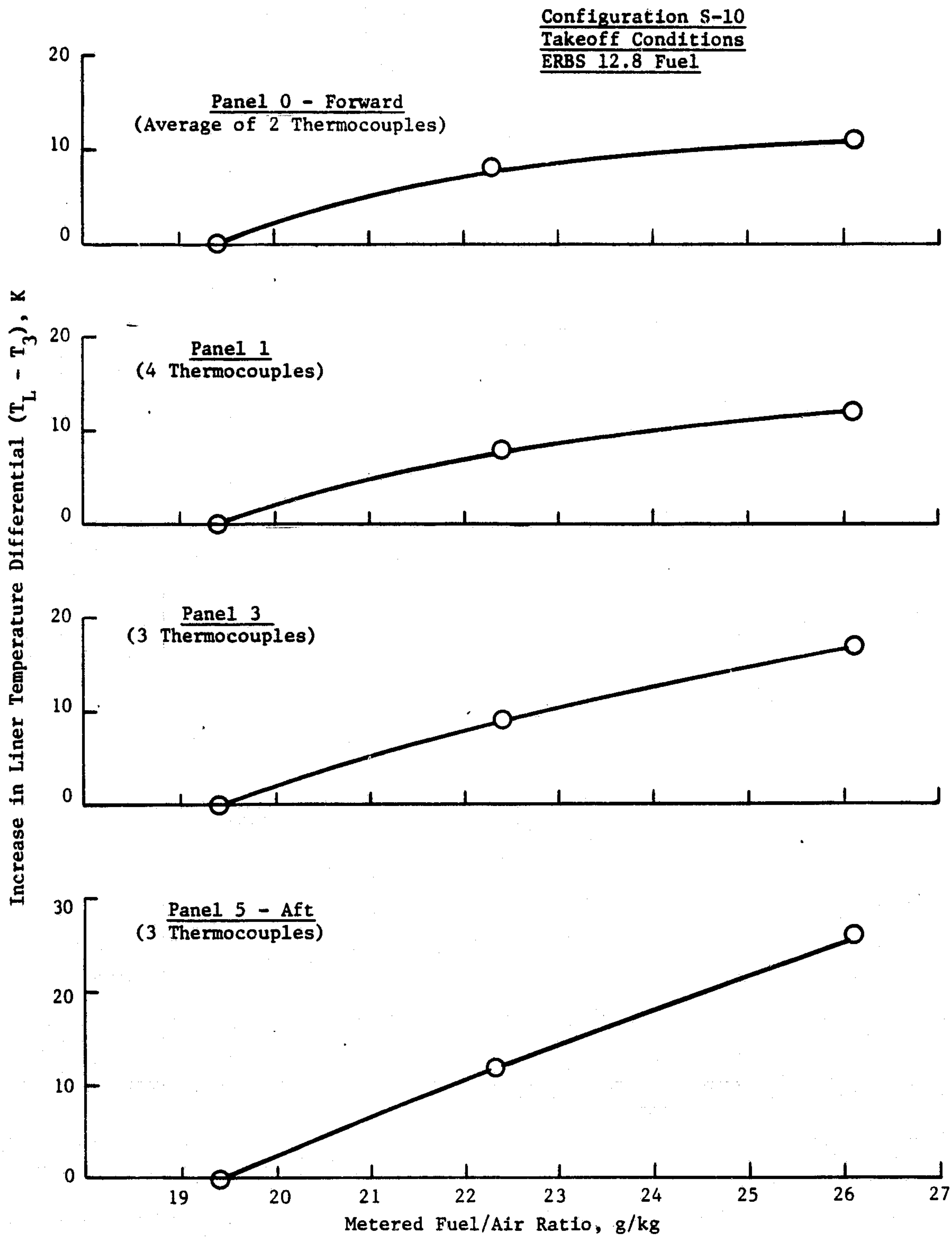

Figure 6-8. Local Fuel/Air Ratio Effects on Single-Annular Combustor Liner Temperatures.

different liner panels as fuel/air ratio was varied at the takeoff operating conditions. With a fuel/air ratio increase of about 35%, average forward panel temperature increased by only about 11%, while average aft panel temperature increased by 26%.

Detailed liner temperature profiles for the single-annular combustor at the takeoff operating conditions on ERBS 12.8 fuel are shown in Figure 6-9. Outer liner temperatures are fairly uniform, both axially and circumferentially, with slightly higher temperatures occurring on the aft end of the liner. Inner liner temperatures tend to drop off toward the aft end of the liner. Peak measured liner temperatures, which occurred on the aft panel of the outer liner, were only about 245 K above combustor inlet temperature. This is a peak liner metal temperature of about 1050 K at standard day takeoff, which is well below the program goal of 1150 K peak liner temperature.

Measured primary zone radiant heat flux for the single-annular combustor is shown as a function of power level in Figure 6-10. Heat flux increases monotonically with inlet temperature and does not show a strong effect of increased idle fuel/air ratio with fuel staging, which was apparent with measured liner temperatures. The effect of variation in fuel/air ratio on radiant heat flux at takeoff conditions is weak, as shown in Figure 6-11. If effective primary zone airflow is assumed to include swirler and primary dilution, plus 50% of dome cooling (cooling air entrained by swirler and dilution airflows) the primary zone is stoichiometric at a fuel/air ratio of 24 g/kg. The variation from 19.4 g/kg to 26.1 g/kg in Figure 6-11 then represents operation in a fairly narrow band of primary zone equivalence ratios, with stoichiometric operation (and peak flame radiation) falling in the center of this band, and a large variation in radiant heat flux is not expected.

The exit temperature profiles measured with Configuration S-10 are shown in Figure 6-12. These profiles are based on temperatures calculated from individual gas samples obtained during operation at the takeoff condition while burning ERBS 12.8 fuel. Pattern and profile factors both approach, but do not meet, the program goals. Peak temperatures are center peaked, while the profile is outboard peaked. Comparison of these

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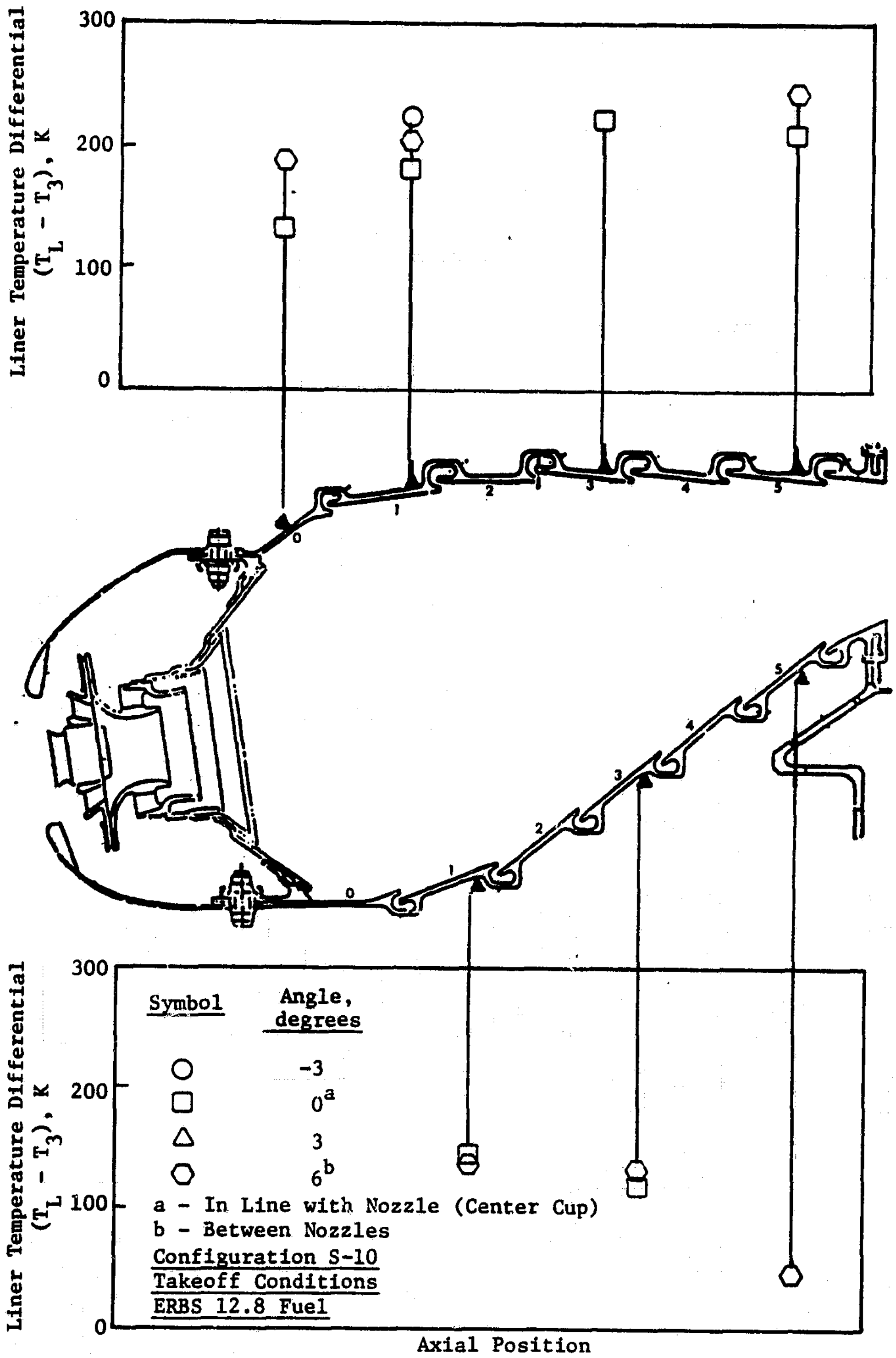

Figure 6-9. Detailed Single-Annular Combustor Temperatures.

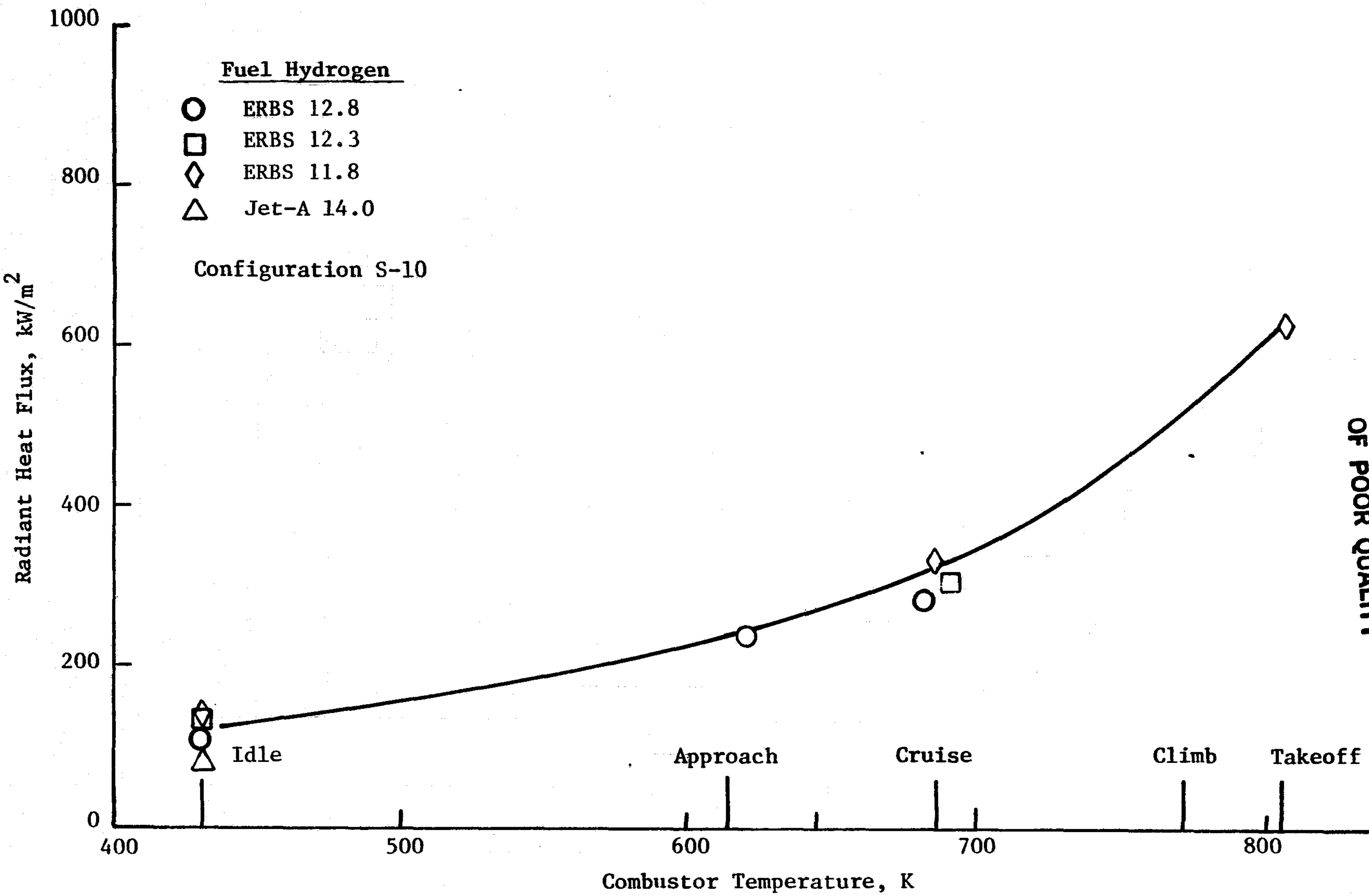

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Figure 6-10. Single-Annular Combustor Primary Zone Radiant Heat Flux.

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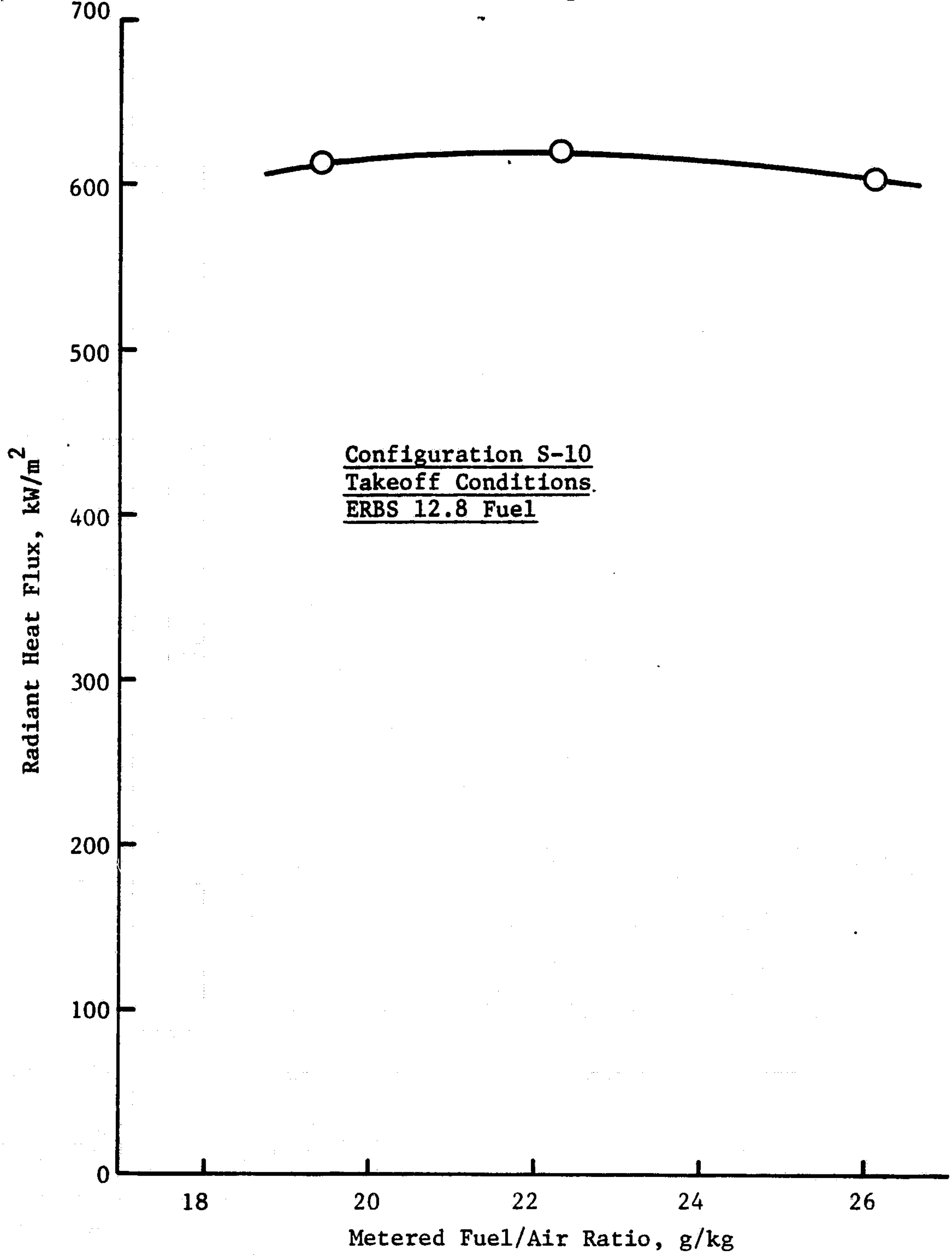

Figure 6-11. Variation in Single-Annular Combustor Primary Zone Flame Radiation with Fuel/Air Ratio (Takeoff Operating Conditions).

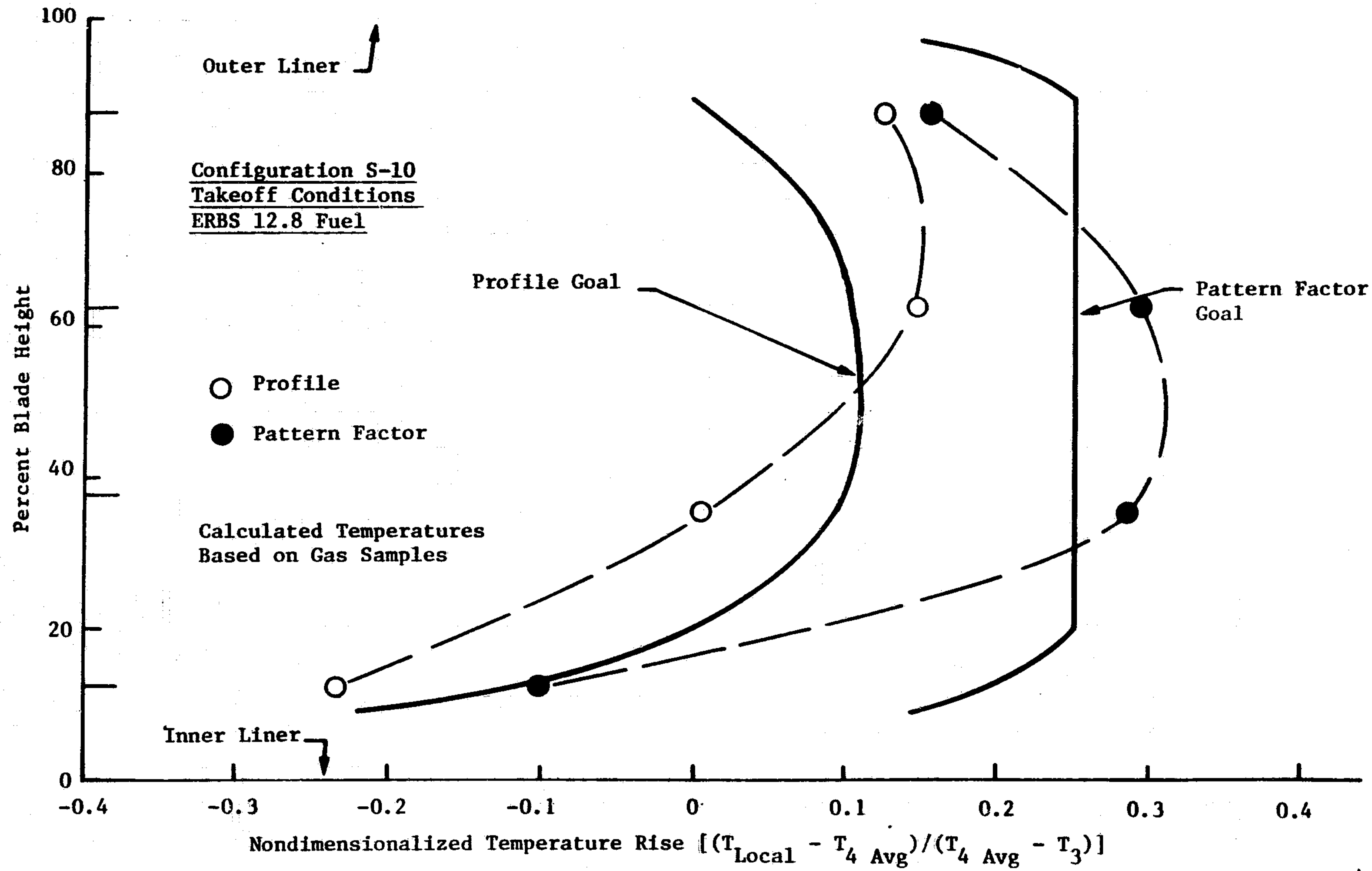

Figure 6-12. Single-Annular Combustor Exit Temperature Profiles.

sector test results with exit temperature profiles measured in full-annular tests with a similar combustor configuration indicates that the magnitude of pattern factors obtained in the sector tests are very close to those obtained in the full-annular tests. However, the sector tests tend to provide a less accurate estimate of the profile factor because of the small number of samples obtained. Full-annular profile factors are typically based on 1680 total measurements (seven radial immersions at 240 different circumferential locations) compared to 16 locations (from immersions at four circumferential locations) in the sector tests. Full-annular results indicate that the true profile factor for this combustor would be between 0.07 and 0.10, compared to the sector test value of 0.14.

Altitude relight/blowout test results for the single-annular combustor (Configuration S-9) are presented in Figure 6-13. Data obtained with Jet-A fuel have been selected for this figure to allow comparison with full-annular test results. Blowout occurred above the target relight envelope except at the lowest Mach number where blowout was just slightly below the goal. Agreement between the sector and full-annular test results is also excellent, except at the low Mach number. It is thought that the discrepancy between full-annular and sector test results at the low Mach number is due in part to unsteady airflow at the very low airflow levels. This test point was difficult to set and maintain in the Cell A3 facility because the sector airflow level was below levels for which the air supply system valving and metering components were sized. The single-annular combustor very nearly meets the altitude relight goal, based on blowout results.

Lean blowout was also measured at the 4% idle operating conditions. Here, blowout occurred at a fuel/air ratio of 6.4 g/kg with uniform burning on ERBS 12.8 fuel. This is below the level of about 7.5 g/kg needed for engine deceleration. The blowout fuel/air ratio would be expected to be reduced to about 4.3 g/kg with 4/2 fuel staging.

Postrun photographs of the single-annular combustor Configuration S-10 dome is shown in Figure 6-14. Both the dome and fuel nozzles were

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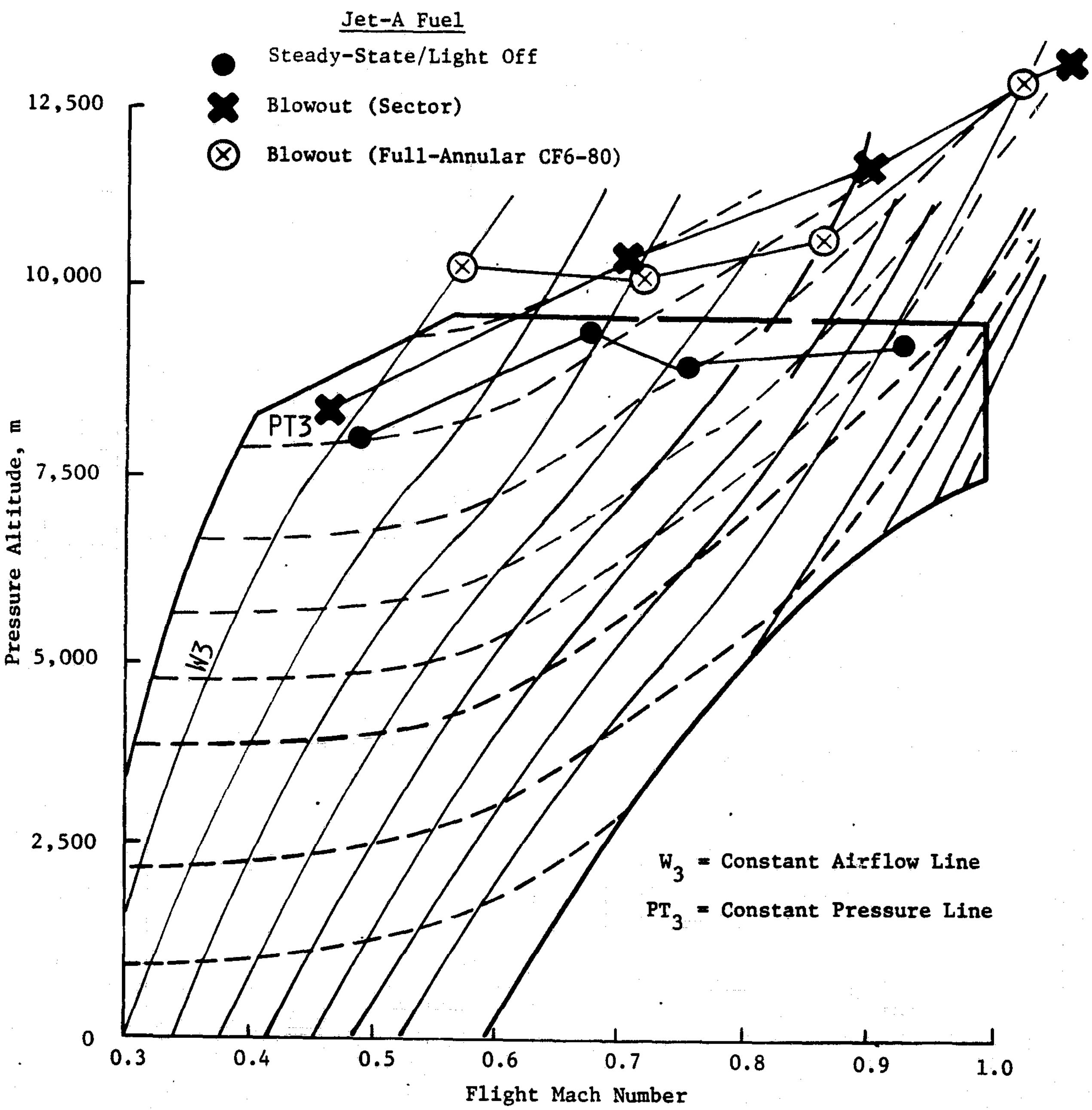

Figure 6-13. Single-Annular Combustor Altitude Blowout.

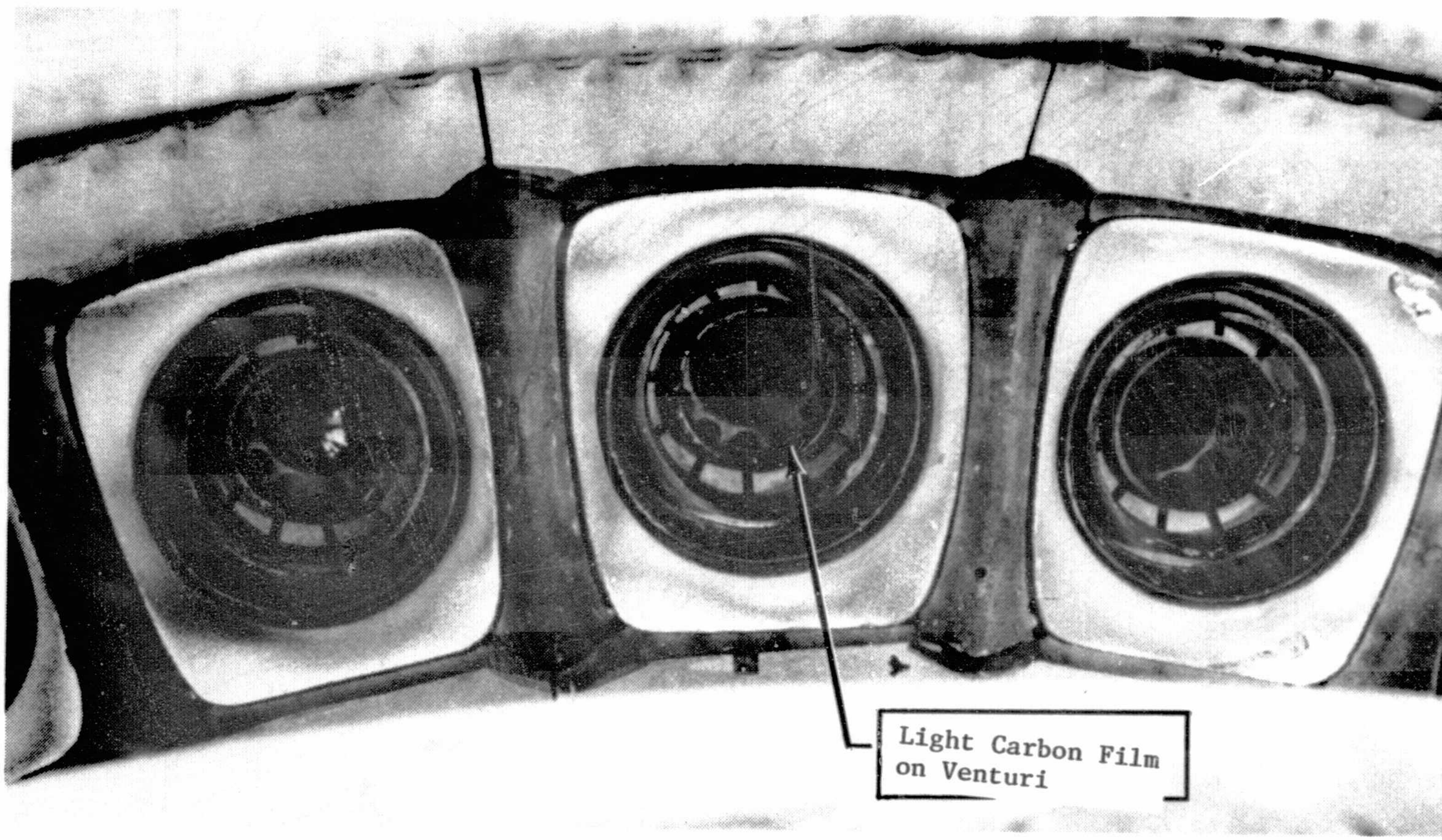

Figure 6-14. Post Run Photograph of Single-Annular Combustor Dome.

virtually carbon-free except for a very light coating of carbon on the inside of the swirler verturi. Combustor liner surfaces were also carbon-free. The thermal barrier coatings used in this combustor were also in excellent condition after the test.

6.1.2 Combustor Development Progress

A total of 10 different single-annular combustor configurations were tested. These configurations have been described in Section 4.0. Significant progress was made in improving the combustor emissions and performance characteristics of this combustor concept.

6.1.2.1 Emissions

Emissions results obtained with the different single-annular combustor configurations on ERBS 12.8 fuel are summarized in Figure 6-15. In the baseline test, CO, NO_x, and smoke were all above the program goals with this fuel. Smoke was furthest above the goal and was considered to be the most important of the emissions since EPA requirements for smoke are already in effect and because increased smoke levels are generally indicative of increased flame radiation within the combustor. Therefore, initial combustor development efforts with Configurations S-2 through S-5 were aimed primarily at smoke reduction.

Improved fuel atomization at high power levels proved effective in reducing both smoke and NO_x emissions. As shown in Figure 6-16, these emissions were reduced in Configuration S-2, where the proportion of fuel flow to the primary fuel nozzle orifice was increased. This had the effect of narrowing the fuel nozzle spray angle and reducing the fuel droplet size. Although a smoke reduction of about 25% was achieved with this atomization change, this was insufficient to meet the program goal.

Additional smoke reduction was sought in Configuration S-3 through S-5 by variation in the liner dilution hole patterns. Smoke was reduced below the goal level in Configuration S-5 by moving the primary dilution holes forward on both the inner and outer liners and using dilution "thimbles" as described in Section 4.0.

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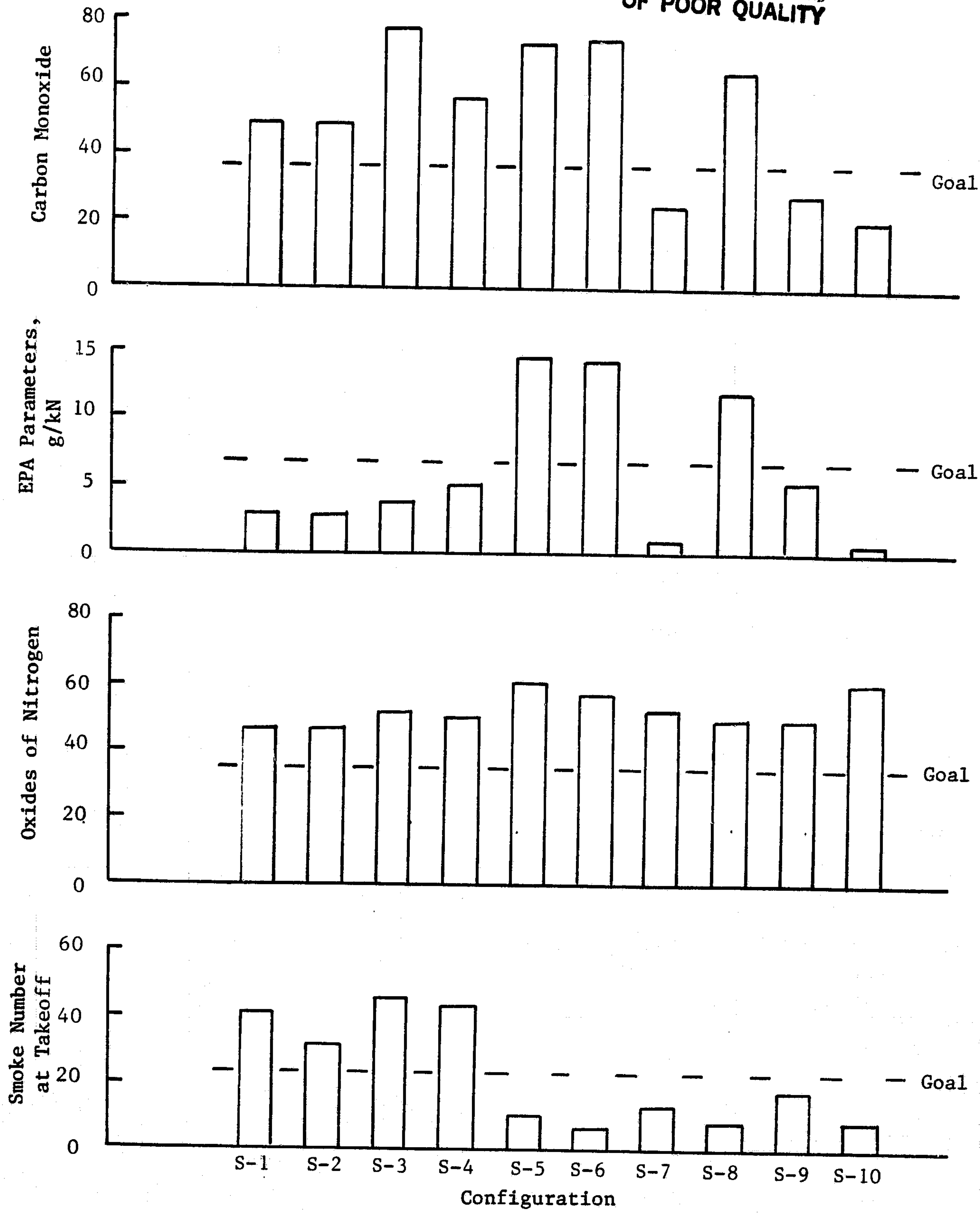

Figure 6-15. Single-Annular Combustor Emissions with ERBS 12.8 Fuel.

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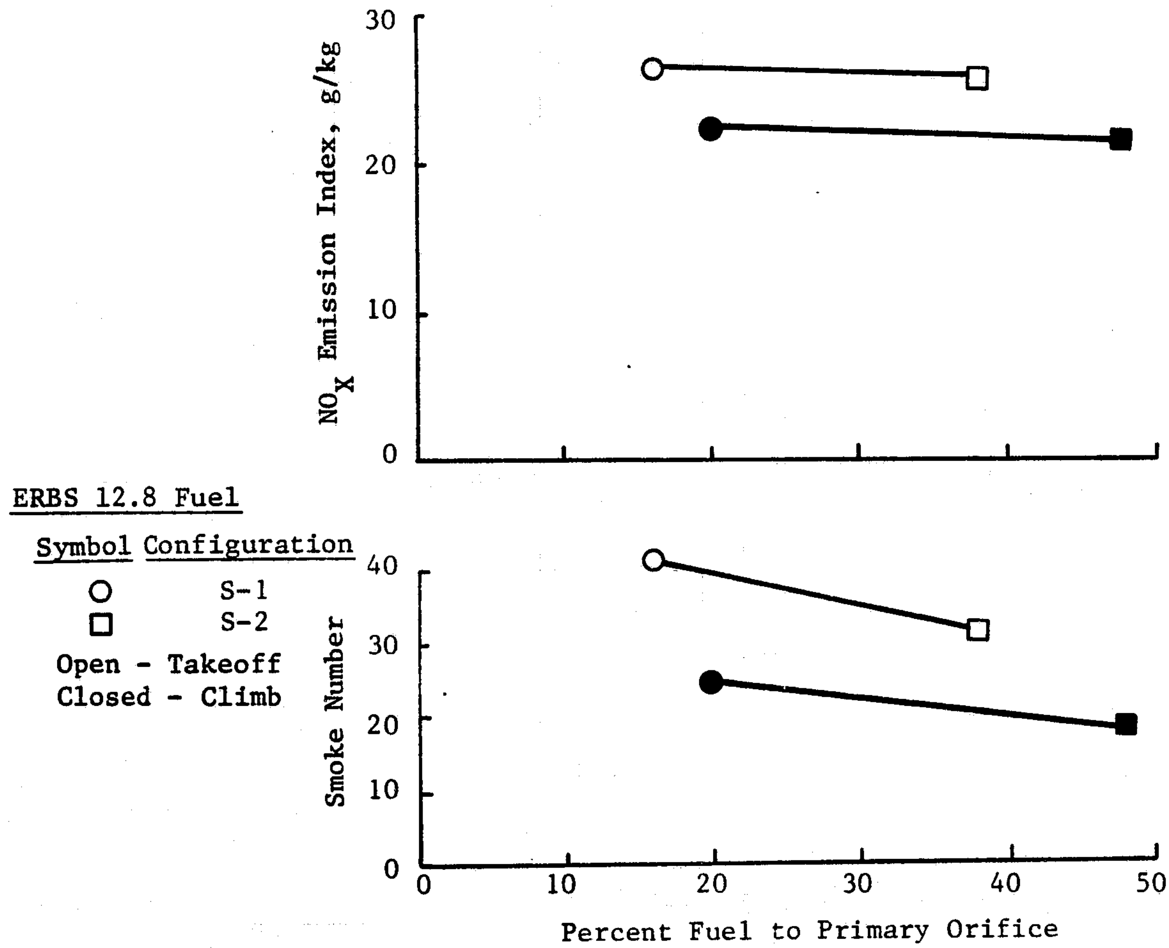

Figure 6-16. Effect of Fuel Atomization on Single-Annular Combustor High Power Emissions.

Although the dilution pattern of Configuration S-5 was successful in reducing smoke levels, all gaseous emissions were well above the levels measured with the baseline combustor. Therefore, Configurations S-6 and S-7 were defined with the objective of reducing gaseous emissions, particularly CO and HC, while maintaining the low smoke levels achieved with Configuration S-5.

Configuration S-6 incorporated reduced fuel nozzle shroud flow for improved fuel atomization at low power in order to reduce CO and HC emissions at idle, but no significant emissions improvement was obtained. In Configuration S-7, the primary dilution hole flows and locations were very similar to S-5 and S-6, but the dilution thimbles were replaced by simple punched holes in an attempt to reduce quenching by the strong primary dilution jets at idle conditions. This modification was successful in reducing CO and HC to levels below the program goals. Smoke levels increased significantly with the weaker dilution jets but were still comfortably below the program goals.

Configuration S-8 incorporated a "flattened" dome contour and an advanced swirler design. Both of these features were intended to improve primary zone mixing for generally improved emissions and performance. Smoke and NO_x were reduced slightly, but CO and HC were increased above program goals. Since very limited development opportunity remained in the Phase I program after Configuration S-8 was evaluated, no further effort was made to develop this advanced swirler design, and the baseline swirler was used in Configurations S-9 and S-10.

Configurations S-9 and S-10 were based on S-7 and also incorporated the flattened dome contour and thermal barrier coatings for improved performance. Both of these configurations met all emission goals except for NO_x.

In summary, significant emissions development progress was made on the single-annular combustor during the course of this program. The carbon monoxide EPA parameter was reduced by 60% relative to the baseline combustor to a level which meets the program goal with a 45% margin. The

unburned hydrocarbon EPA parameter was reduced by more than 80% to a level which meets the program goal with more than 90%. For both CO and HC, fuel staging at idle is needed to meet the goals. Smoke level was reduced by 75% to a smoke number of about nine at takeoff, which meets the program goal with a margin of more than 50%. The only emission which failed to meet the goal was NO_x. Reduction of NO_x emissions from the single-annular combustor was not stressed during the Phase I test program because no NO_x requirement was proposed for engines manufactured before 1984, and work with the single-annular combustor was used primarily to define retrofittable modifications to in-use engines. Based on previous emissions reduction programs, it is thought that an advanced design concept such as the double-annular and variable-geometry combustors will be needed to meet the program goals for NO_x.

6.1.2.2 Performance

Some of the key performance results obtained with the various single-annular combustor configurations burning ERBS 12.8 fuel are compared in Figure 6-17.

Except for Configuration S-8, all of the single-annular combustor configurations met or very closely approached the peak liner temperature goal. It is thought that the significantly higher liner temperature in Configuration S-8 is due to the wider fuel spray angle with the advanced swirler. This would tend to increase fuel concentrations adjacent to the combustor liners, thereby increasing liner temperature. Liner temperatures were significantly reduced when primary dilution thimbles were used to improve primary zone mixing (Configurations S-5 and S-6) and when thermal barrier coatings were used (Configurations S-9 and S-10). Improved fuel atomization (Configuration S-2) also reduced liner temperatures to a lesser extent.

Idle blowout fuel/air ratios were below the goal for all configurations except for S-5 (and presumably S-6, which was not evaluated for blowout). Apparently, the primary dilution thimble feature, which reduced liner temperatures and smoke by improved primary zone mixing at higher

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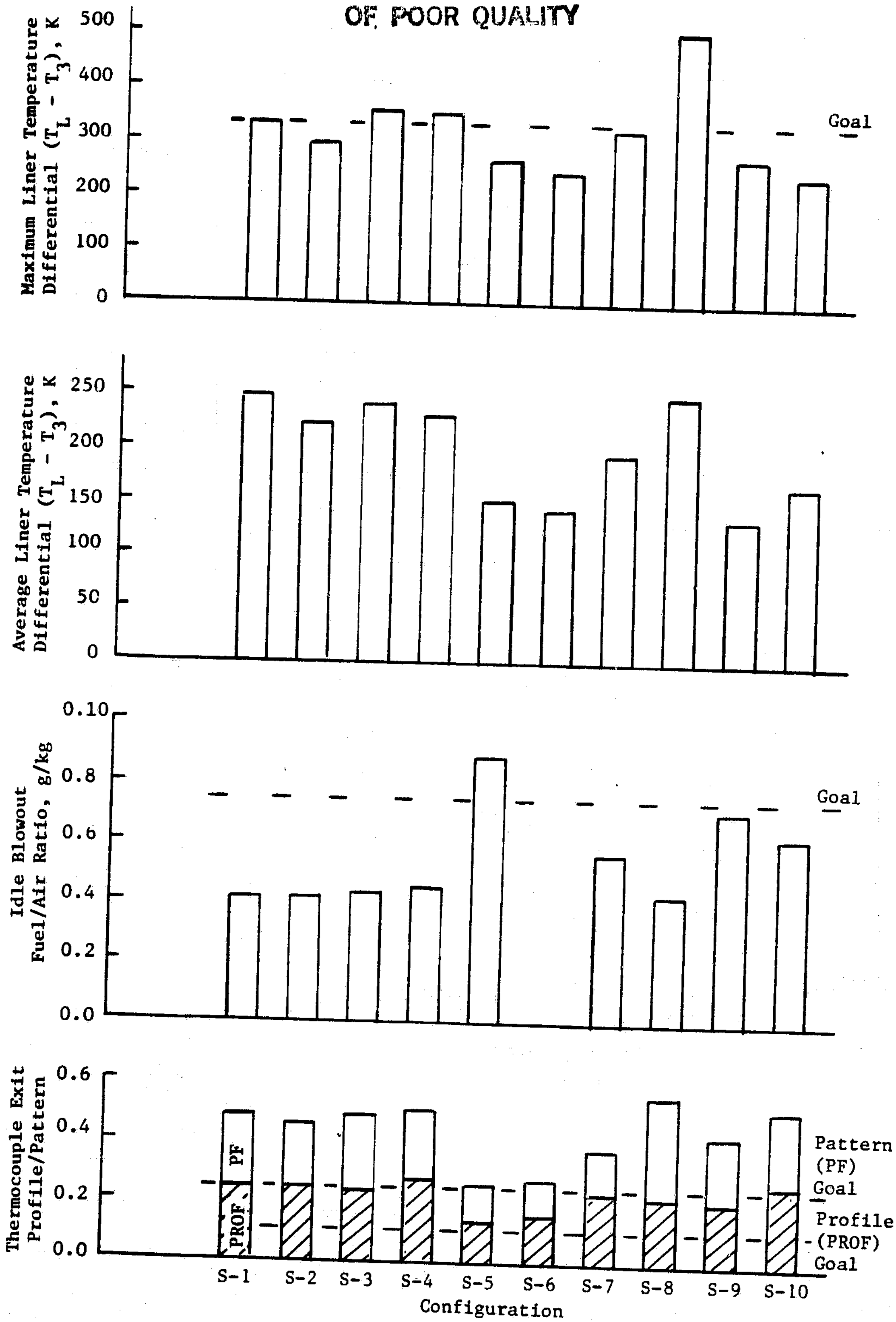

Figure 6-17. Single-Annular Combustor Performance.

power, also eliminated rich central core regions downstream of each swirl cup which could support combustion at low fuel/air ratios at idle conditions. This result is consistent with the higher CO and HC levels obtained with this configuration. In general, the configurations which had the lower smoke emission levels also had the higher idle blowout fuel/air ratios. The one exception to this trend is Configuration S-8, which incorporated the advanced swirler. It is thought that lean blowout was improved in this configuration due to the presence of rich regions near the combustor liners, generated by the higher spray angle swirl cups. These rich regions provided good stability even though the rich central core region which causes smoke emissions was eliminated.

None of the exit profiles as measured with thermocouples in the sector combustor actually met program goals. However, it should be noted that the exit profiles in this figure were based on a very small number of measurement positions (three rakes, each having four thermocouple probes), and that these temperature rakes were located within 6° of the sector combustor sidewalls where some distortion can occur. More representative profiles were obtained for selected sector configurations by taking individual gas samples, as shown in Figure 6-12. Comparison with detailed annular combustor test results with similar combustor configurations indicates that both profile and pattern factors measured with the thermocouple probes in the sector are well above true values determined in the full-annular tests. For example, full-annular tests of the baseline single-annular combustor indicate that this configuration closely approached the program goals, while Figure 6-17 indicates that reductions of about 50% in both pattern and profile factors are needed. Although the values obtained in these sector tests are high, they do indicate exit profile trends with changes in design features. Exit temperature results are consistent with other emissions and performance results in that the lowest pattern and profile factors were obtained with the combustor configurations having the primary dilution thimbles, which seem to result in the most uniform primary zone mixture. In other configurations, temperature profiles tended to be more uniform when smoke levels and liner temperature

were lower, again indicating improved primary zone mixing. As would be expected, Configuration S-8, which had low smoke but also had indications of primary zone nonuniformity (including high liner temperatures and low blowout fuel air ratio), had somewhat higher pattern and profile factors.

Other aspects of combustor performance were generally good with all configurations of the single-annular combustor concept. Combustor efficiencies were above 99% at idle for all configurations which met the idle emissions goals and were above 99.5% at all other operating conditions. Pressure drop for all configurations were within 0.5 point of the 4.7% design goal and were well below the program goal of 6%. Combustor carboning was not a problem with any of the single-annular combustor configurations.

In summary, the final single-annular combustor configuration currently meets all engine performance requirements, although additional exit temperature profile development would be required to meet the pattern and profile factor goals. During the course of this Phase I program, liner cooling performance and combustion efficiency at idle were significantly improved. The lean blowout fuel/air ratio at idle was increase, but was still below the program goal, while exit temperature pattern and profile factors were virtually unchanged.

Emissions and performance trade-offs were identified as a function of primary zone uniformity. Improved primary zone uniformity, whether achieved by atomization (Configuration S-2) or dilution mixing (Configurations S-5 and S-6) resulted in reduced smoke, liner temperature, and pattern and profile factors at high power operating conditions. However, very intense primary zone mixing also resulted in increased CO and HC emissions and higher blowout fuel/air ratios, apparently due to the reduction of rich regions needed to promote stable, efficient combustion at low combustor inlet temperatures and pressures. The final single-annular configuration provided a good balance between these conflicting effects and also incorporated thermal barrier coatings for improved liner cooling performance.

6.1.3 Fuel Effects

Five of the ten single-annular combustor configurations were evaluated on two or more of the test fuels, with the complete range of hydrogen contents having been evaluated on the baseline combustor configuration (S-1) and the final, best, test configuration. For these two configurations, several key emissions and performance parameters have been analyzed as a function of fuel hydrogen content. Results of these analyses are discussed in the following paragraphs. Fuel hydrogen content was the primary fuel property which was varied in this test series and was, therefore, selected as the independent variable for all of these fuel effects analyses. As discussed in Section 5.3, several of the fuel chemical properties varied with hydrogen content, while fuel fluidity and front end volatility did not vary a great deal from fuel to fuel. Where it is probable that variations in emissions or performance characteristics are due to fuel properties other than hydrogen content, these other potential effects have also been noted.

6.1.3.1 Emissions

Carbon monoxide emissions from single-annular combustor Configurations S-1 and S-10 at the idle, cruise, and climb conditions are shown in Figure 6-18. Idle CO emission data were not obtained for the full range of fuel hydrogen content with Configuration S-1, so no idle results are shown for that configuration. Carbon monoxide emission levels obtained with the final, best, single-annular configurations were well below the baseline levels at all operating conditions. A slight tendency toward increased CO with increasing fuel hydrogen content was observed at the higher power conditions, but CO levels at those conditions were low, and the change was insignificant in terms of the EPA parameter. No truly significant fuel effects on CO emissions were observed with this concept.

Hydrocarbon emissions are shown as a function of fuel hydrogen content and operating condition in Figure 6-19. Because of the very low HC levels obtained with this concept, any fuel effects are obscured by normal data scatter. However, levels are so low that only an extremely strong

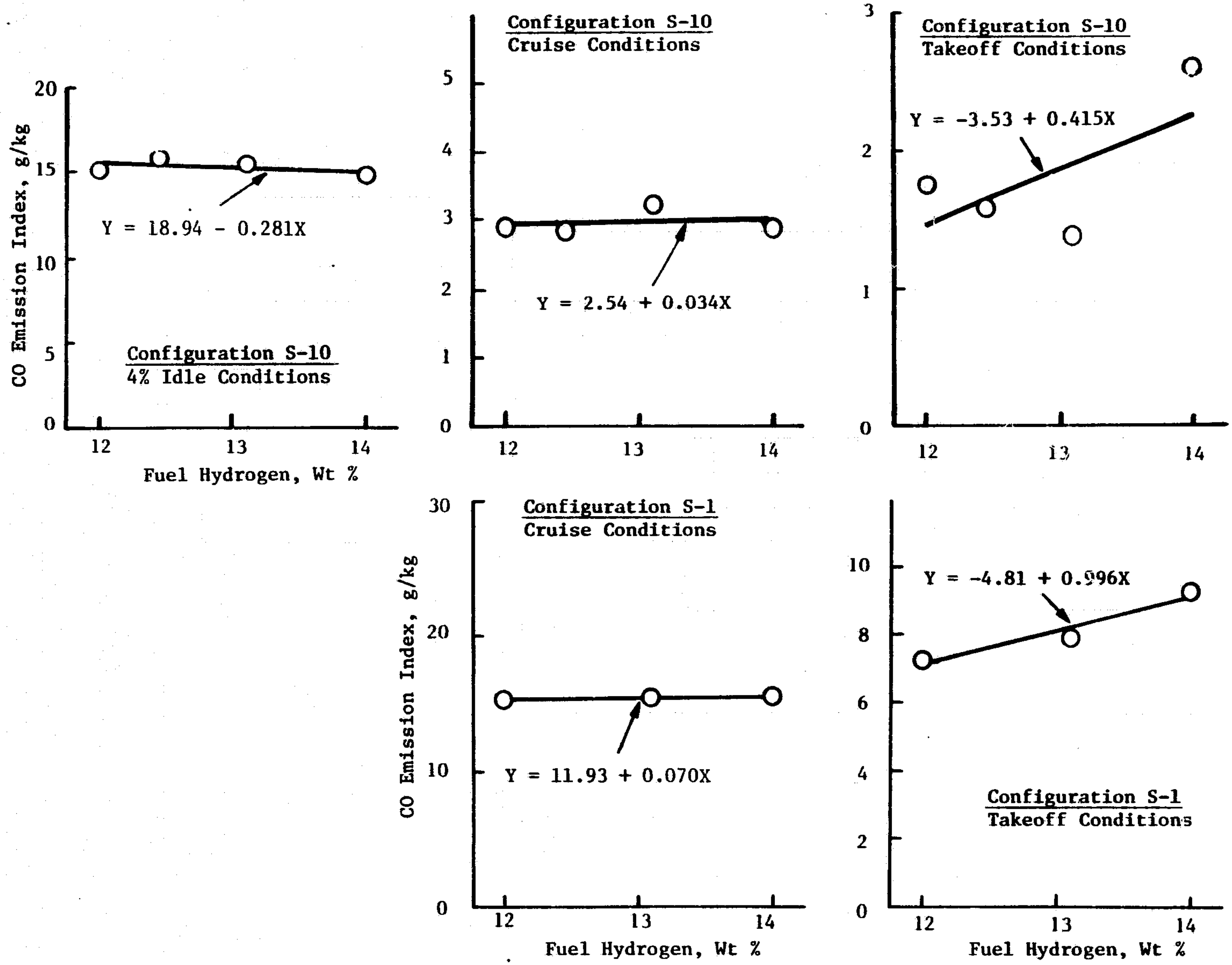

Figure 6-18. Effect of Fuel Hydrogen Content on Single-Annular Combustor Carbon Monoxide Emissions.

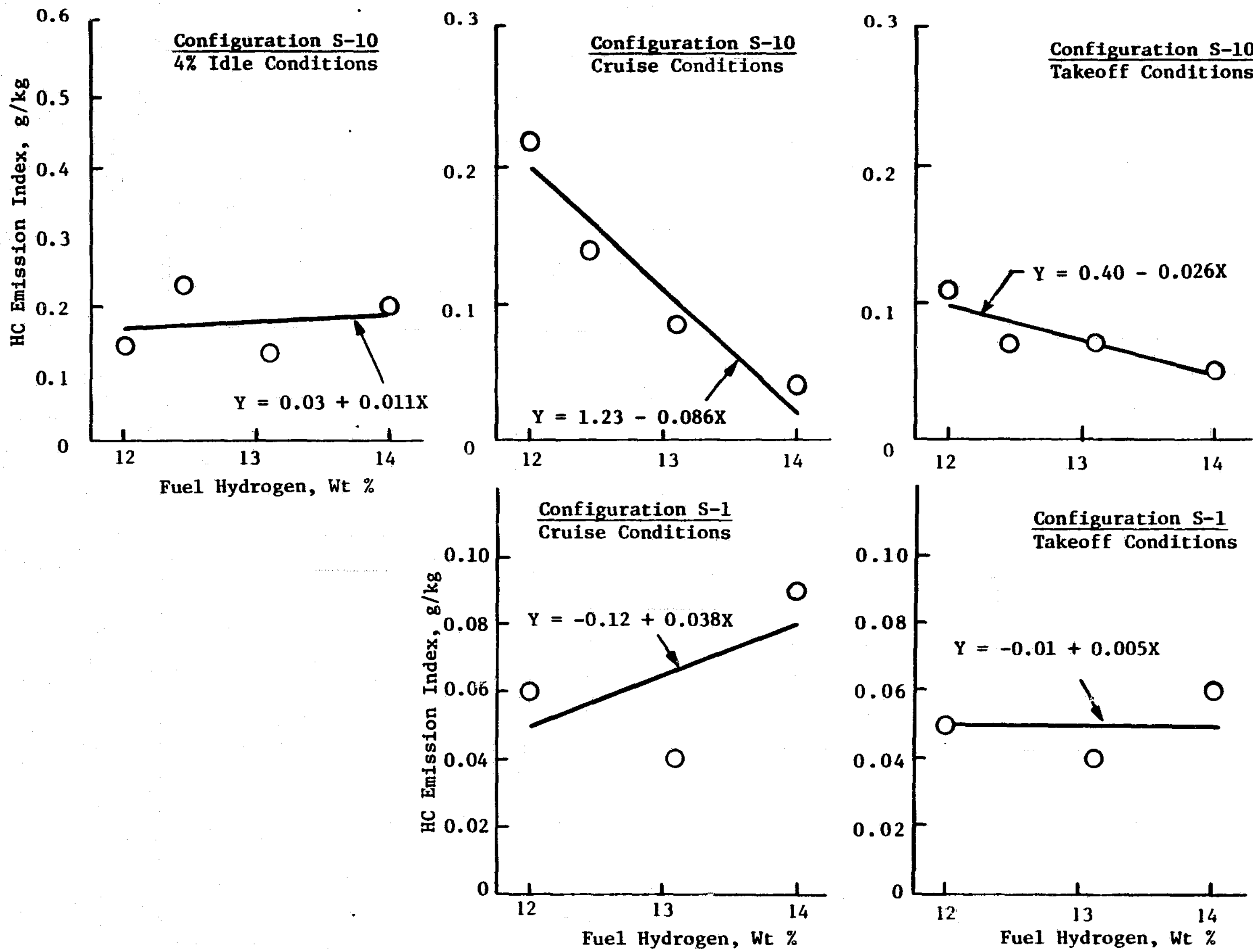

Figure 6-19. Effect of Fuel Hydrogen Content on Single-Annular Combustor Unburned Hydrocarbon Emissions.

fuel effect would significantly effect the EPA parameter for this emission. Therefore, it has been concluded that over the range of fuel properties studied, fuel effects on HC emissions were not significant.

Emissions of NO_x were consistently found to decrease with increasing fuel hydrogen content at all operating conditions, as shown in Figure 6-20. On the average for the cases shown, NO_x levels increased at the rate of about 7% for each percent reduction in fuel hydrogen content, using the Jet-A fuel as a baseline. This is consistent with results of previous fuel effects studies.

Smoke emissions are shown as a function of fuel hydrogen content and power level in Figure 6-21. A definite trend toward increased smoke with decreasing hydrogen content is evident at idle, and a weaker effect in the same direction was observed at cruise operating conditions, although there is considerable data scatter at this latter point. At takeoff power levels, where the smoke levels are highest, any fuel effect is lost in the data scatter. The scatter in these data does not appear to be associated with fuel effects other than hydrogen content. Generally, smoke does tend to increase with decreasing hydrogen content, but this effect becomes weaker as power level is increased. These same trends have been observed in previous studies (References 2, 3, and 4).

In summary, both smoke and NO_x emissions from the single-annular combustor were increased as fuel hydrogen content was decreased. No significant effect on CO and HC emissions was observed. Emissions sensitivity to fuel effects was about the same, on a percentage basis, for the best configuration of this concept as it was for the baseline configuration.

6.1.3.2 Performance

The effects of fuel hydrogen content on average and maximum combustor liner metal temperature differentials (metal temperature less combustor inlet temperature) at the idle, cruise, and takeoff operating conditions are shown for the baseline and best single-annular combustor configuration

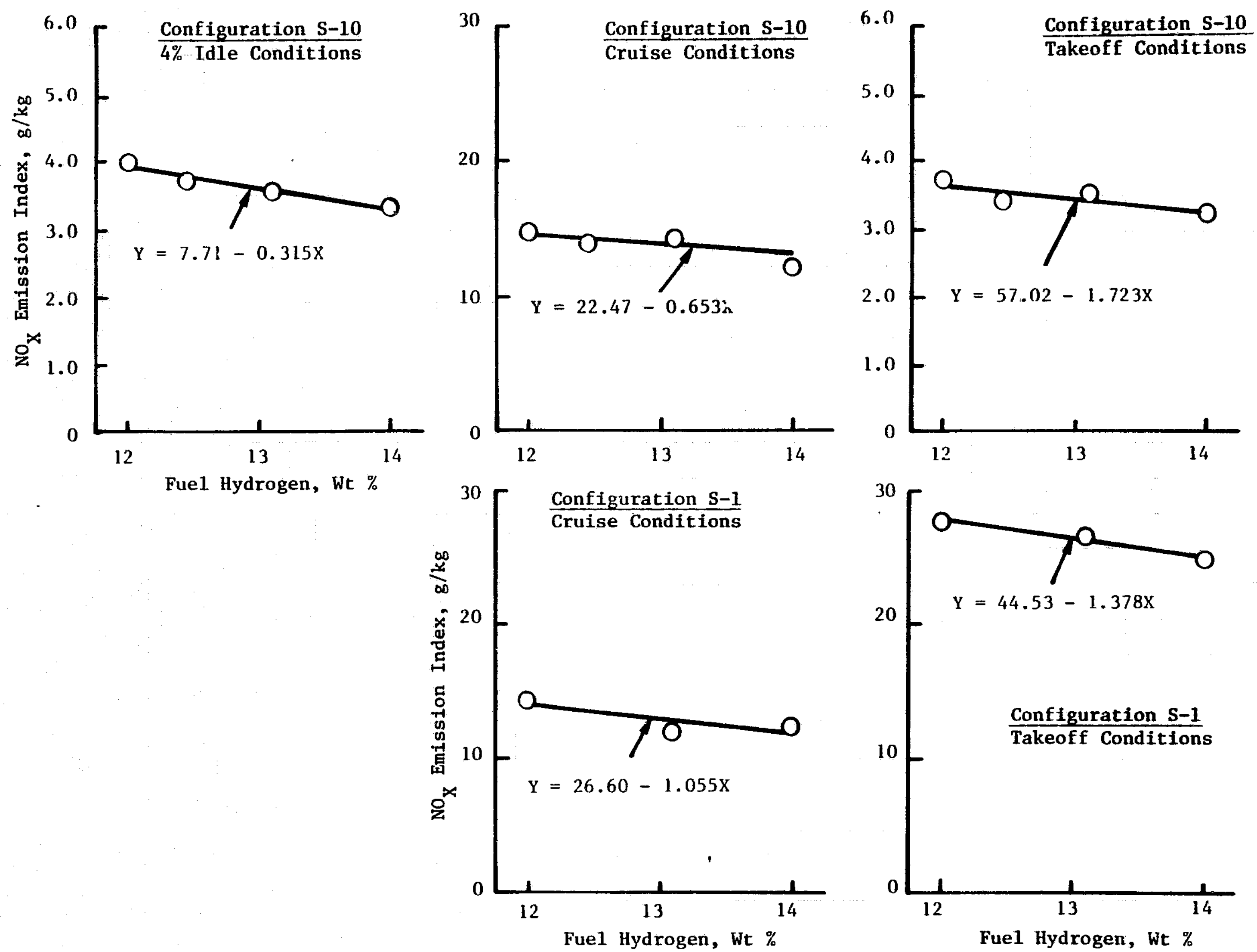

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Figure 6-20. Effect of Fuel Hydrogen Content on Single-Annular Combustor Oxides of Nitrogen Emissions.

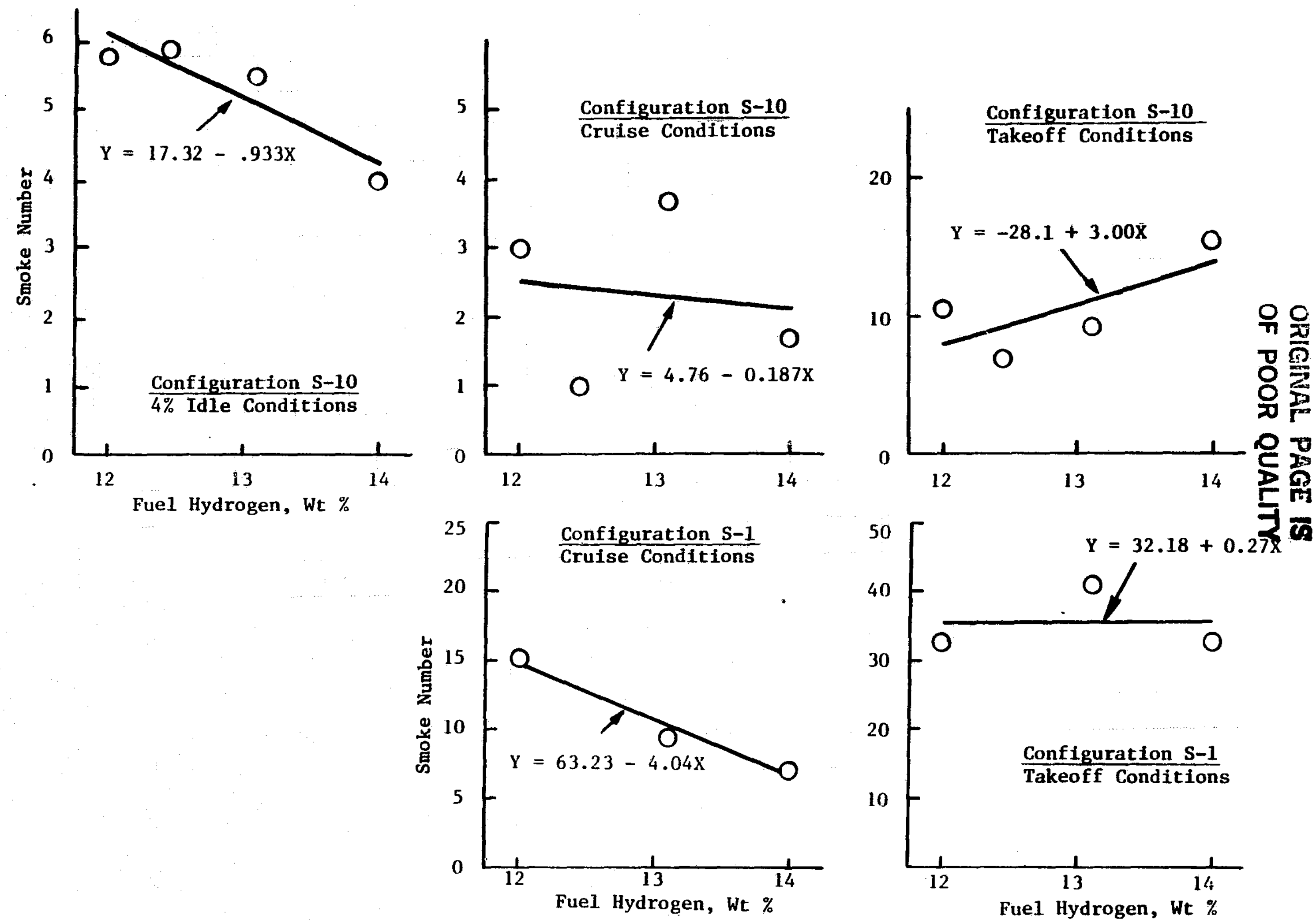

Figure 6-21. Effect of Fuel Hydrogen Content on Single-Annular Combustor Smoke Emissions.

in Figures 6-22 and 6-23. Both maximum and average liner temperatures increase with decreasing hydrogen content at all operating conditions with both combustor configurations. Other observations are that (1) both average and peak liner temperatures for Configuration S-10 are significantly lower than for the baseline configuration; (2) Configuration S-10 is less sensitive to fuel hydrogen content than the baseline configuration; and (3) senstitivity to fuel hydrogen content tends to decrease as engine power level is increased.

The effects of fuel hydrogen content on primary zone radiation levels from single-annular combustor Configuration S-10 is shown in Figure 6-24. Data were not obtained for all fuels at all three of the power levels shown because the sapphire rod "light pipe" failed during the test run with this configuration. Sapphire rod durability was a problem throughout the test series because the rods were brittle and often cracked during the test runs due to thermal growth-caused distortion. It was also found that calibration of the sapphire rod/pyrometer package was changed when the combustor was ignited due to wetting of the surface of the walls with fuel. Once the initial cold start was completed, the pyrometer output appeared to be consistent, with no further change in calibration with time. Therefore, while the absolute radiation levels shown in Figure 6-24 are not necessarily accurate, the relative radiation levels measured with different fuel and operating conditions are believed to be meaningful.

The measured radiation shows the same trends with fuel type and operating conditions as liner temperature. That is, radiation increases with decreasing fuel hydrogen content, but the sensitivity to hydrogen content is reduced as power level is increased. This is also the same trend that was observed with smoke emissions. Thus the results are self-consistent in that smoke, flame radiation, and liner temperatures are all interrelated, and all exhibit the same behavior with changes in fuel hydrogen content and operating conditions. A comparison of radiant heat flux sensitivity and liner temperature sensitivity to changes in fuel hydrogen content is presented in Table 6-1. For Configuration S-10, a 1% change in fuel hydrogen content at idle condition results in a 39.6%

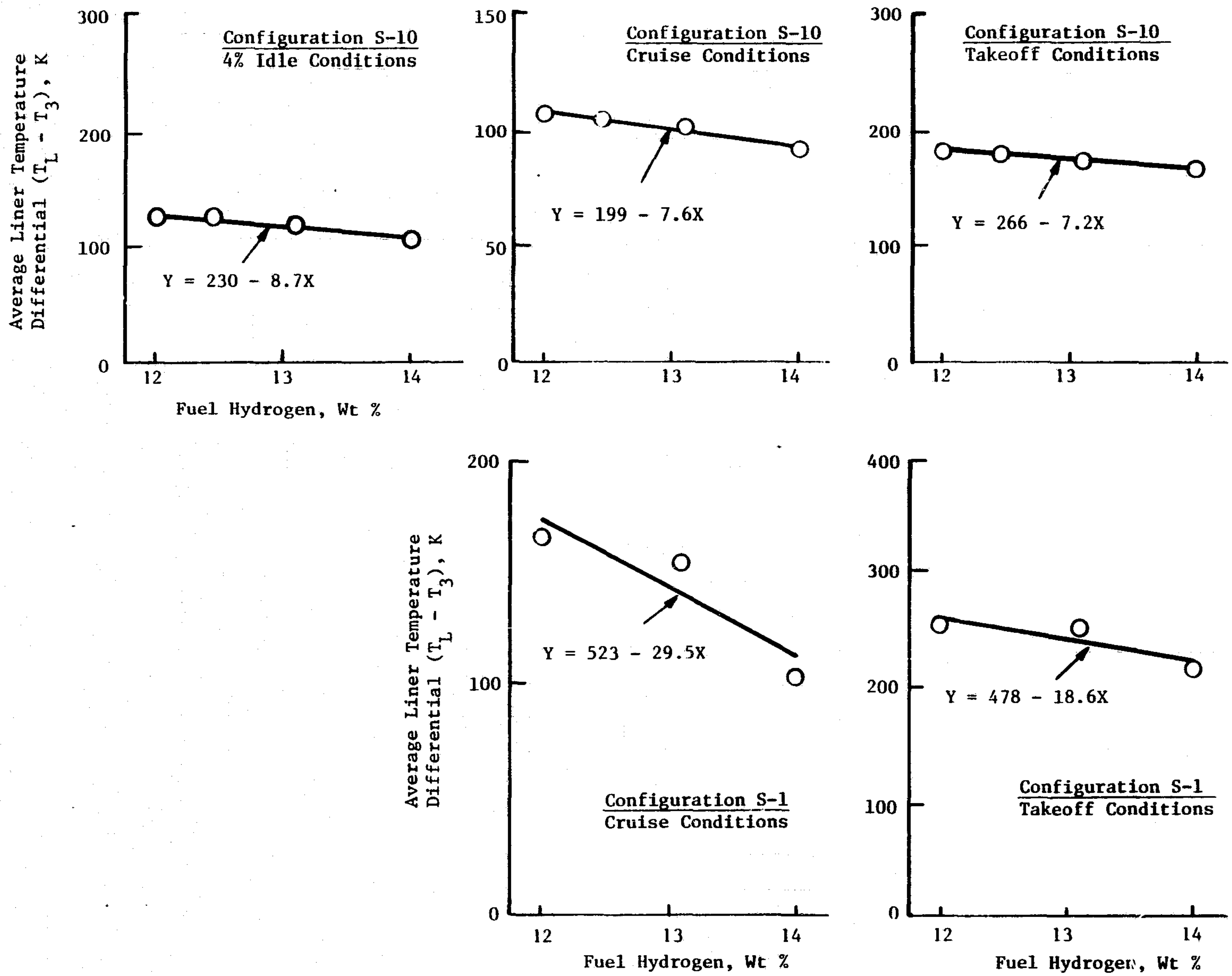

Figure 6-22. Effect of Fuel Hydrogen Content on Single-Annular Combustor Average Liner Temperatures.

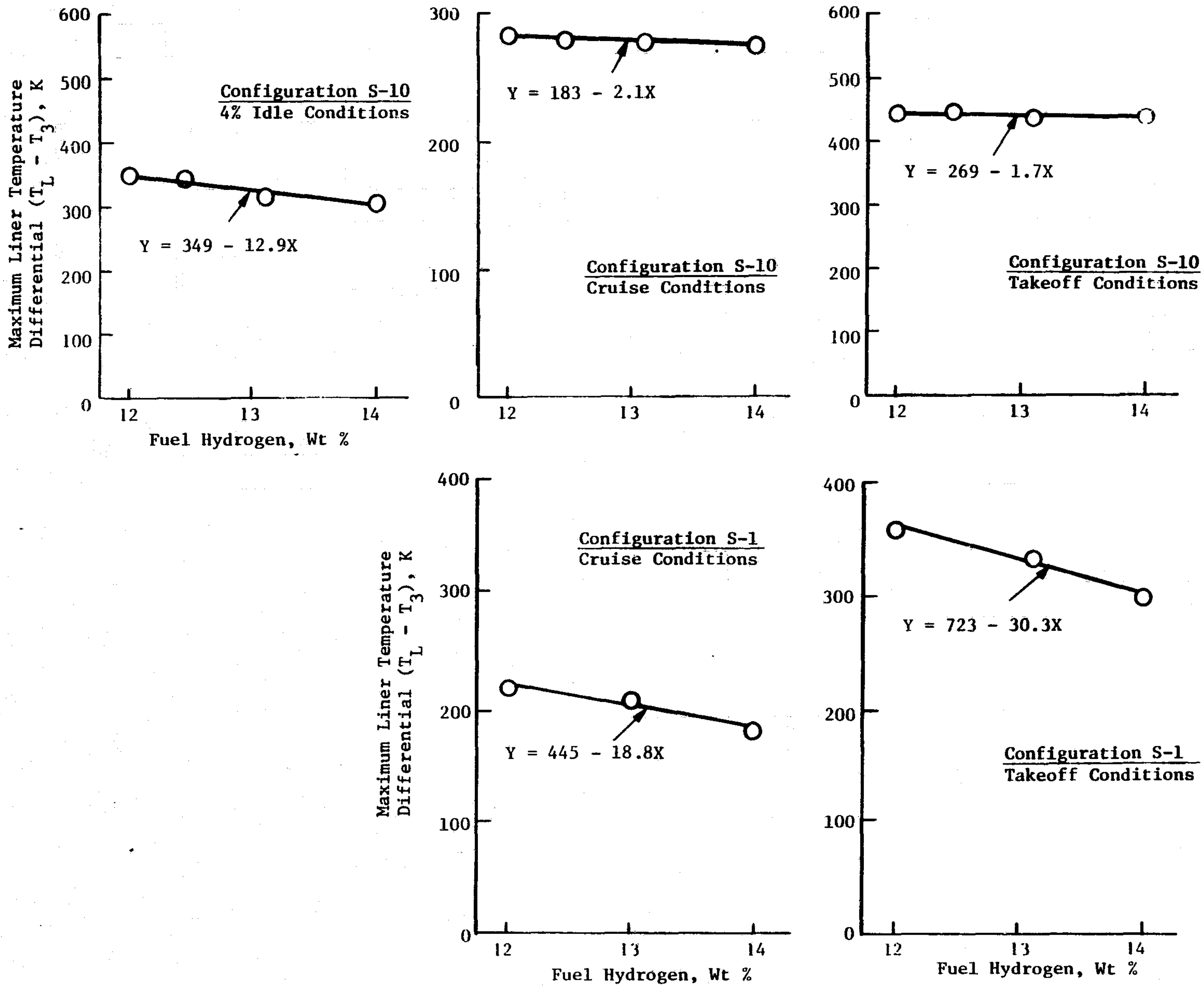

Figure 6-23. Effect of Fuel Hydrogen Content on Single-Annular Combustor Maximum Liner Temperature.

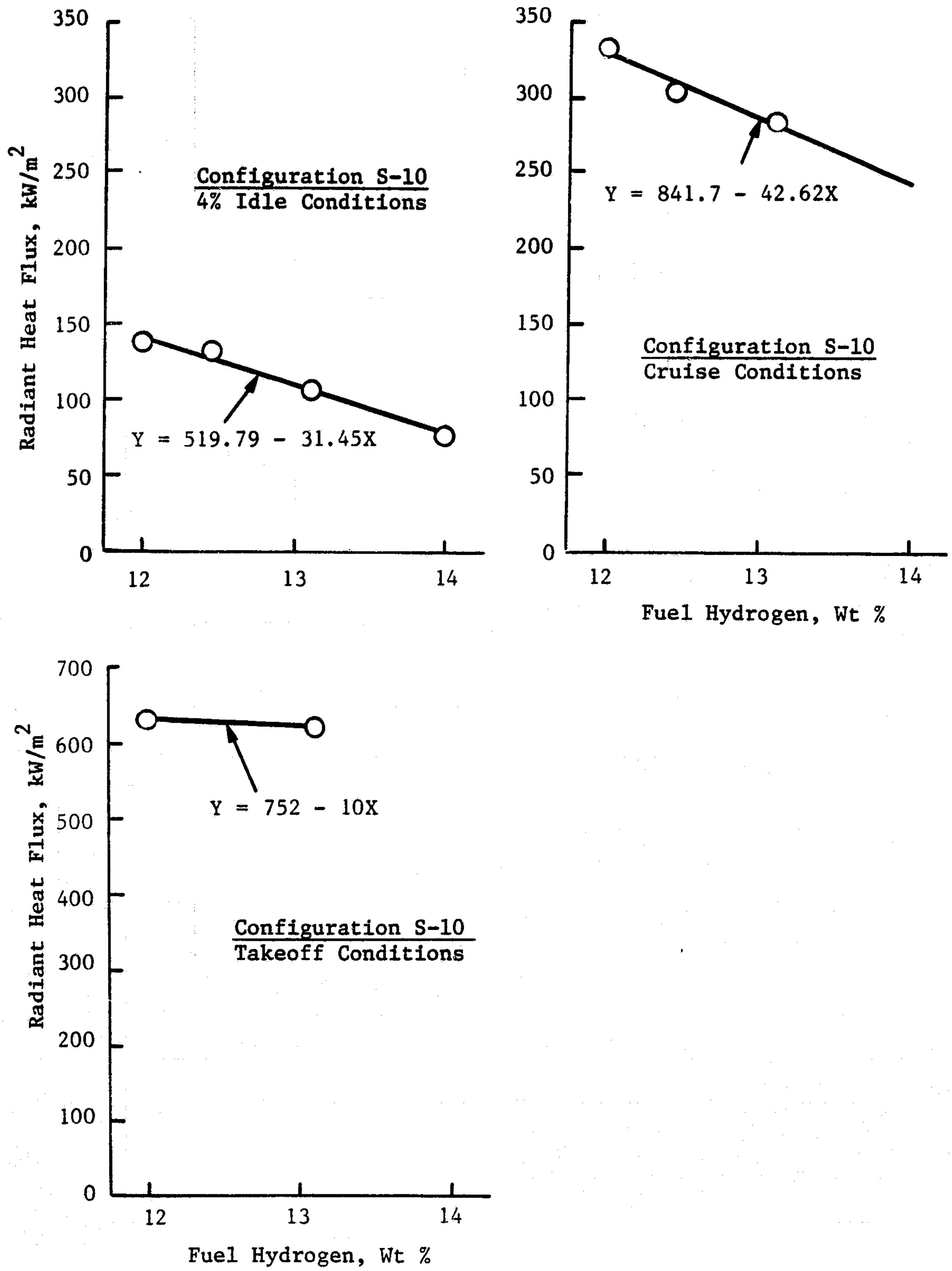

Figure 6-24. Effect of Fuel Hydrogen Content on Single-Annular Combustor Primary Zone Radiation.

Table 6-1. Single-Annular Combustor Sensitivity to Fuel Hydrogen Content at Different Operating Conditions

Operating Condition	Radiant Heat Flux* Sensitivity %	Liner Temperature Sensitivity, %			
		Average Temperature		Maximum Temperature	
	S-10	S-1	S-10	S-1	S-10
Idle	39.6	-	8.0	-	7.7
Cruise	17.4	26.8	8.5	10.5	1.3
Takeoff	1.6	8.6	4.4	10.1	0.7

*Percent Change in Radiant Heat Flux or Liner Temperature Differential (T_{LINER} - T_3) for a 1% Reduction in Fuel Hydrogen Content.

increase in radiation and a 7.7% increase in maximum liner temperature. At takeoff operating conditions, the same change in fuel hydrogen increases radiation by only 1.6%, with an 0.7% increase in maximum liner temperature.

Sensitivity of liner temperatures to changes in fuel hydrogen content also varies with the location on the liner. Local liner metal temperature rise parameters (increase in liner temperature normalized by the liner temperature rise obtained with Jet-A) are shown as a function of inner and outer liner axial and circumferential locations in Figures 6-25 (Configurations S-1 and S-4) and 6-26 (Configuration S-10). Both of these figures represent operation at takeoff conditions. Similar trends were obtained with all of these single-annular combustor configurations. On the outer liner, the forward panel temperatures are far more sensitive to fuel hydrogen content than are the aft panel temperatures. This occurs because the heat transfer due to radiation in the primary zone typically represents more than two-thirds of the total heat load to the forward portion of the liners, while the heat transfer due to radiation in the aft dilution zones is typically less than one-fourth of the total heat load to the aft panels. Thus a change in flame radiation will have a much stronger effect on the forward panels. The inner liner is contoured so that all of the liner panels are exposed to primary zone flame radiation. Therefore, the reduction in sensitivity to fuel effects on aft panel temperature is not as pronounced with the inner liner as with the outer liner. Although the same trends in sensitivity to fuel hydrogen are apparent with all of the single-annular configurations shown, sensitivity is reduced at all locations with Configuration S-10.

Because of the variations in the effect of fuel hydrogen content at different locations within the combustor, the effect of fuel hydrogen content on combustor life will not depend totally on the average sensitivity to fuel hydrogen. Rather, the location of the life-limiting region and the local sensitivity to fuel effects in this region will be of primary importance. For example, if it were assumed that Configuration S-1 was

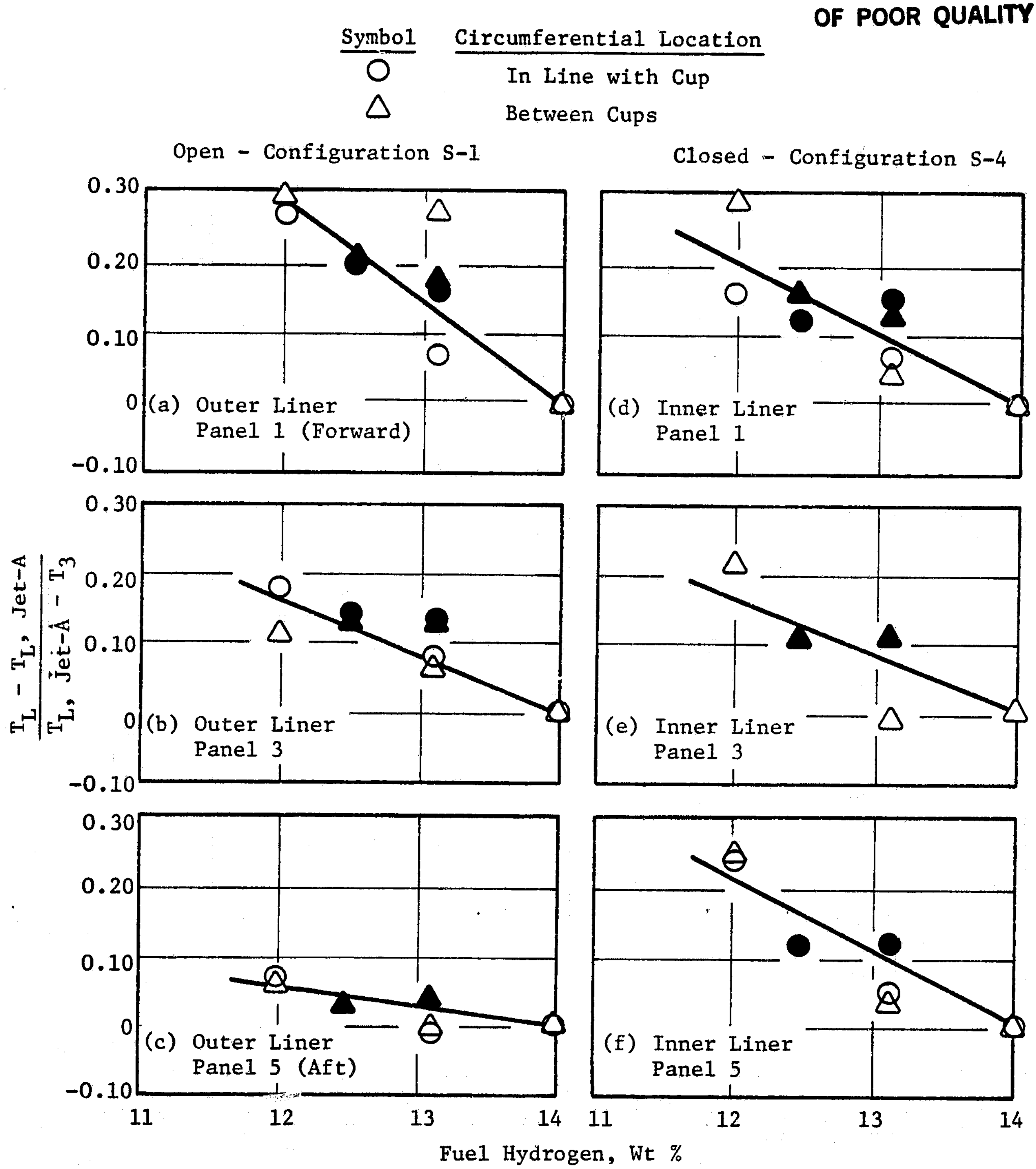

Figure 6-25. Effects of Fuel Hydrogen Content on Local Liner Temperature Parameter - Single-Annular Combustor Configurations S-1 and S-4 (Takeoff Conditions).

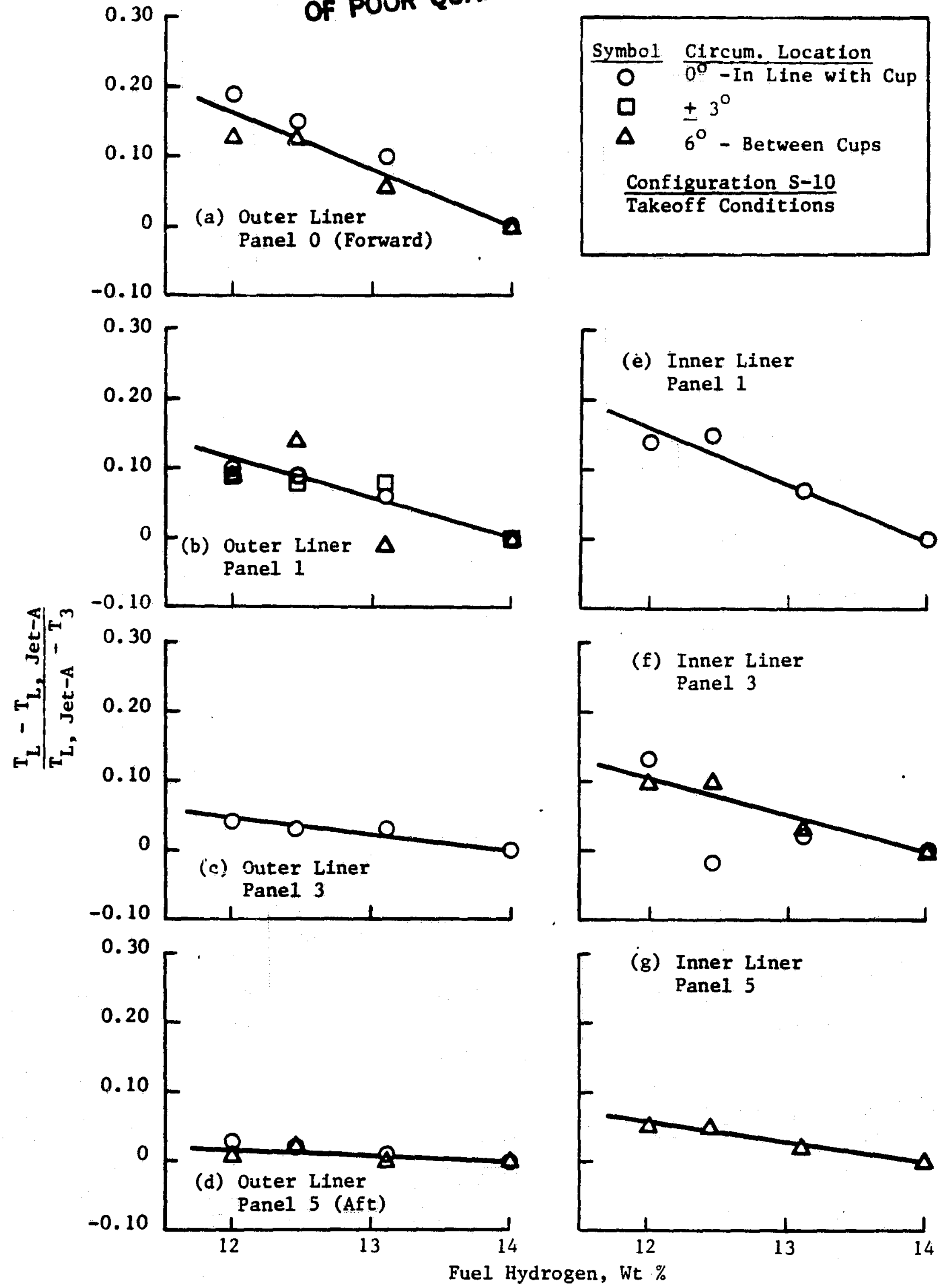

Figure 6-26. Effects of Fuel Hydrogen Content on Local Liner Temperature Parameter - Single-Annular Combustor Configuration S-10.

life-limited by temperatures on Panel 5 of the outer liner and Configuration S-10 was life-limited by temperatures on Panel 0 of the outer liner, fuel hydrogen content would have a much stronger effect on the life of Configuration S-10, even though the average liner temperature effect is less for this configuration. However, in actual test results, Configuration S-10 proved superior to the baseline configuration in that average sensitivity was reduced; peak measured liner temperatures occurred further aft, where local sensitivity was less than the average sensitivity; and both average and maximum temperatures were reduced relative to those measured in the baseline configuration.

Results of the single-annular combustor tests indicate that the sensitivity of liner temperatures to changes in fuel hydrogen content decreases as the smoke emissions level is reduced. This trend is shown in Figure 6-27, where average and maximum liner temperature parameters for operation at takeoff conditions with ERBS 12.8 fuel are shown as a function of measured takeoff smoke number. Thus modifications which reduce smoke levels will also tend to improve fuel flexibility with respect to liner temperature.

The effect on combustor life of changes in liner temperature due to decreased fuel hydrogen content were estimated using the simplified procedure of Reference 18. This procedure basically assumes that (1) low cycle fatigue crack initiation is life-limiting and (2) the pseudoelastic stress is essentially proportional to the thermal gradient which is, in turn, proportional to liner temperature differential (liner temperature less combustor inlet temperature). Combustor life ratios can be estimated from the liner temperature parameter used in Figure 6-27 and combustor service life. This life ratio has been found to be relatively independent of peak metal temperatures, coolant temperatures, and the actual detailed stress calculation. Using this method with appropriate material properties for the CF6-80 combustor and an assumed service life of an inlet temperature of 756 K and a base liner temperature of 1144 K, 500 cycles, life reduction was estimated as a function of liner temperature parameter. Resulting life estimates are shown in Figure 6-28. Using this curve, with the

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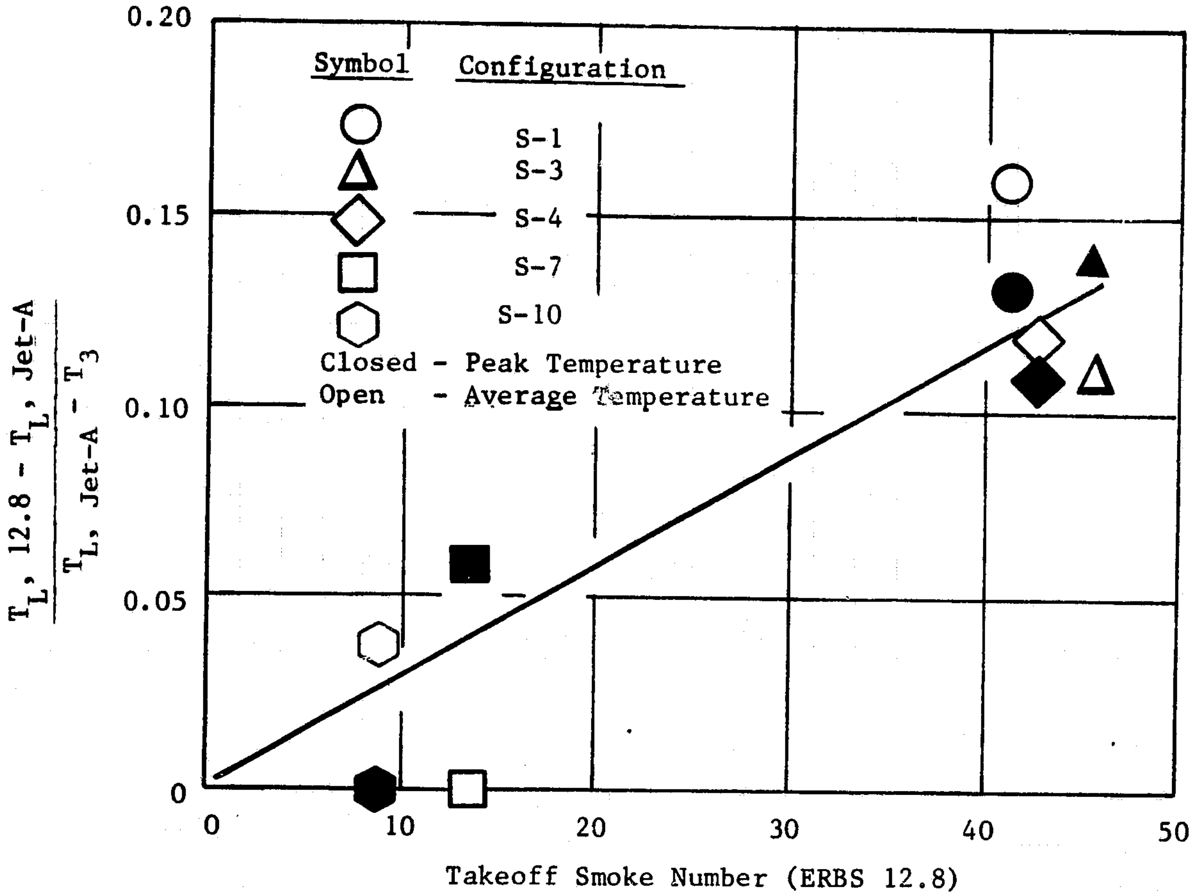

Figure 6-27. Effect of Smoke Level on Liner Temperature Sensitivity to Fuel Type (Takeoff Operating Conditions).

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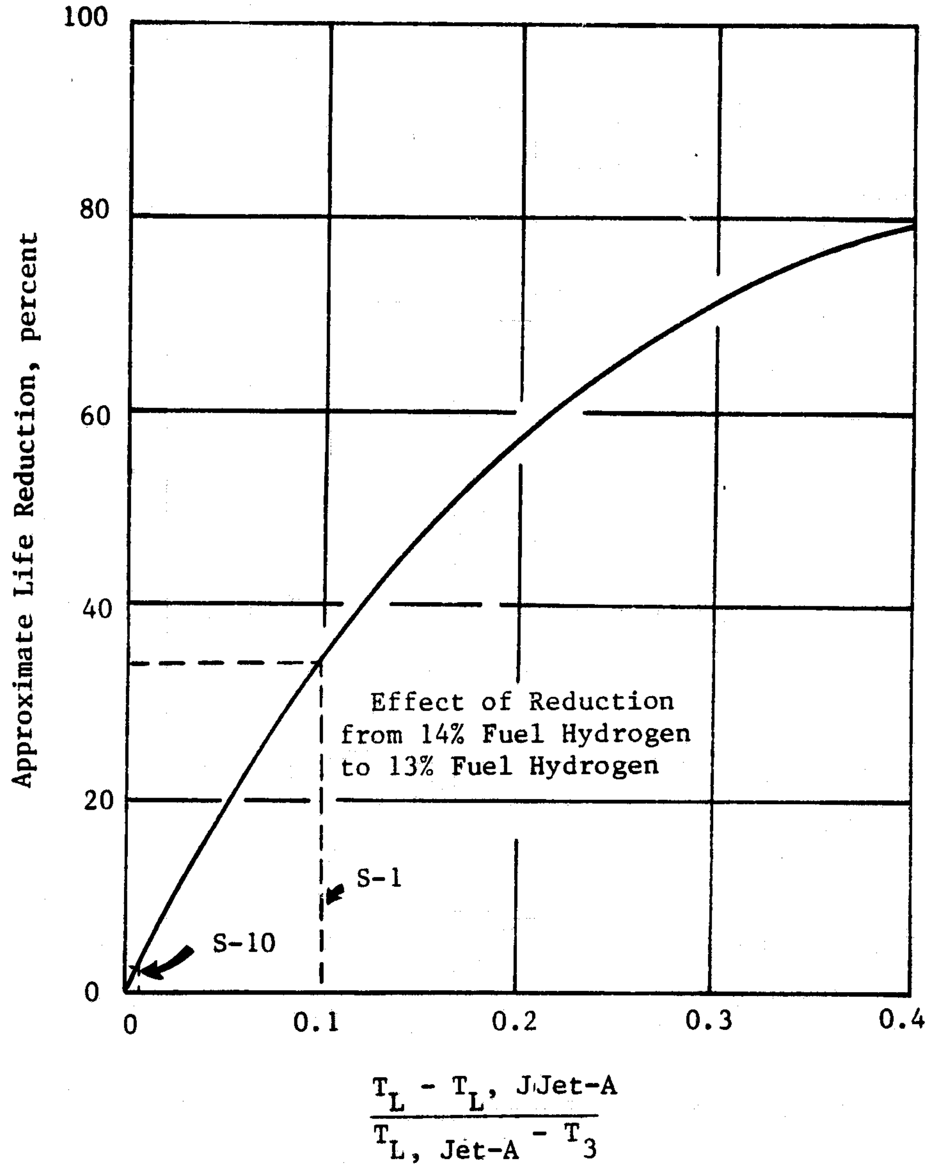

Figure 6-28. Effect of Liner Temperature Parameter on Combustor Life.

maximum liner temperature sensitivities for the baseline and best single-annular combustor configurations at takeoff operating conditions (taken from Table 6-1), predicted combustor life for the baseline configuration is reduced by about one-third in going from a fuel containing 14% fuel hydrogen to one containing 13%, while predicted life for Configuration S-10 is only reduced by about 3% for the same change in fuel hydrogen content. In addition to this reduction in sensitivity, the life of Configuration S-10 would be increased relative to the baseline combustor because both average and maximum liner temperatures were lower in this final configuration.

Other aspects of steady-state performance were not significantly affected by changes in fuel properties. Based on CO and HC emissions, which comprise combustion inefficiency, combustion efficiency was not found to depend on fuel properties. No effect on combustor pressure drop was observed, and pattern and profile factors were not affected, as shown in Figure 6-29.

Combustor blowout, both at idle and at altitude relight conditions, was slightly affected by fuel type, as shown in Figures 6-30 and 6-31. In both cases, the best performance was obtained with the Jet-A fuel, while performance with the ERBS fuels was not as good. Performance of all of the ERBS fuels was similar in each case. As shown in Figure 6-30, idle blowout fuel/air ratios were about 10% higher for the ERBS fuels than for Jet-A. This difference is not critical because blowout fuel/air ratios are below the program goal for all of the fuels.

At altitude relight conditions, blowout consistently occurred at higher pressures (lower pressure altitudes) with the ERBS fuels over the range of airflows evaluated. Again, the ERBS fuels both produced similar results. In this case, the reduction in stability with the ERBS fuels is significant because it is of sufficient magnitude to decrease blowout altitude to levels which are slightly below the goal over much of the flight Mach number range.

The similarity in blowout results obtained with the ERBS fuels suggests that other fuel properties are more important to combustor stability and relight than hydrogen content. In previous studies, relight

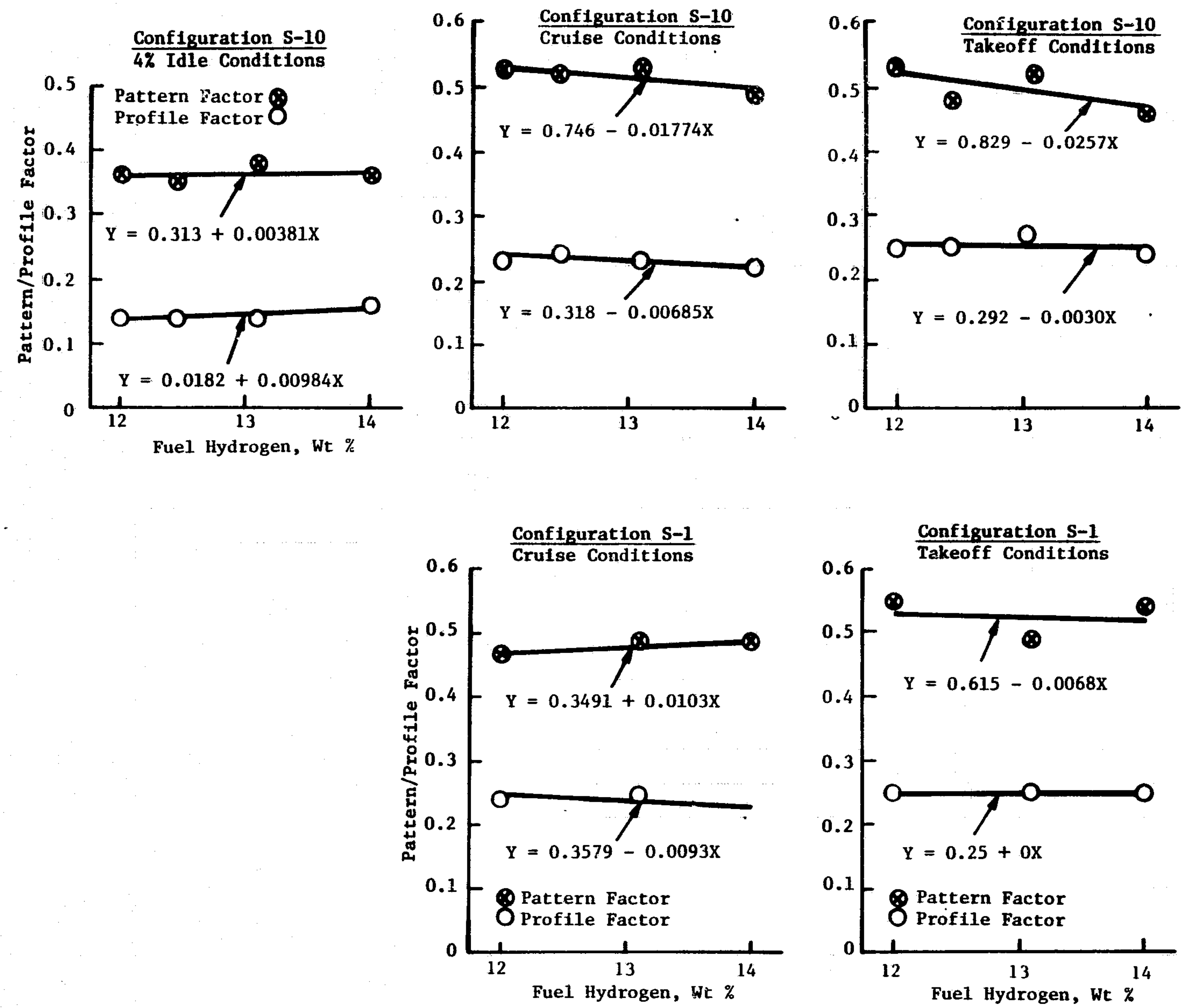

Figure 6-29. Effect of Fuel Hydrogen Content on Single-Annular Combustor Exit Temperature Profiles.

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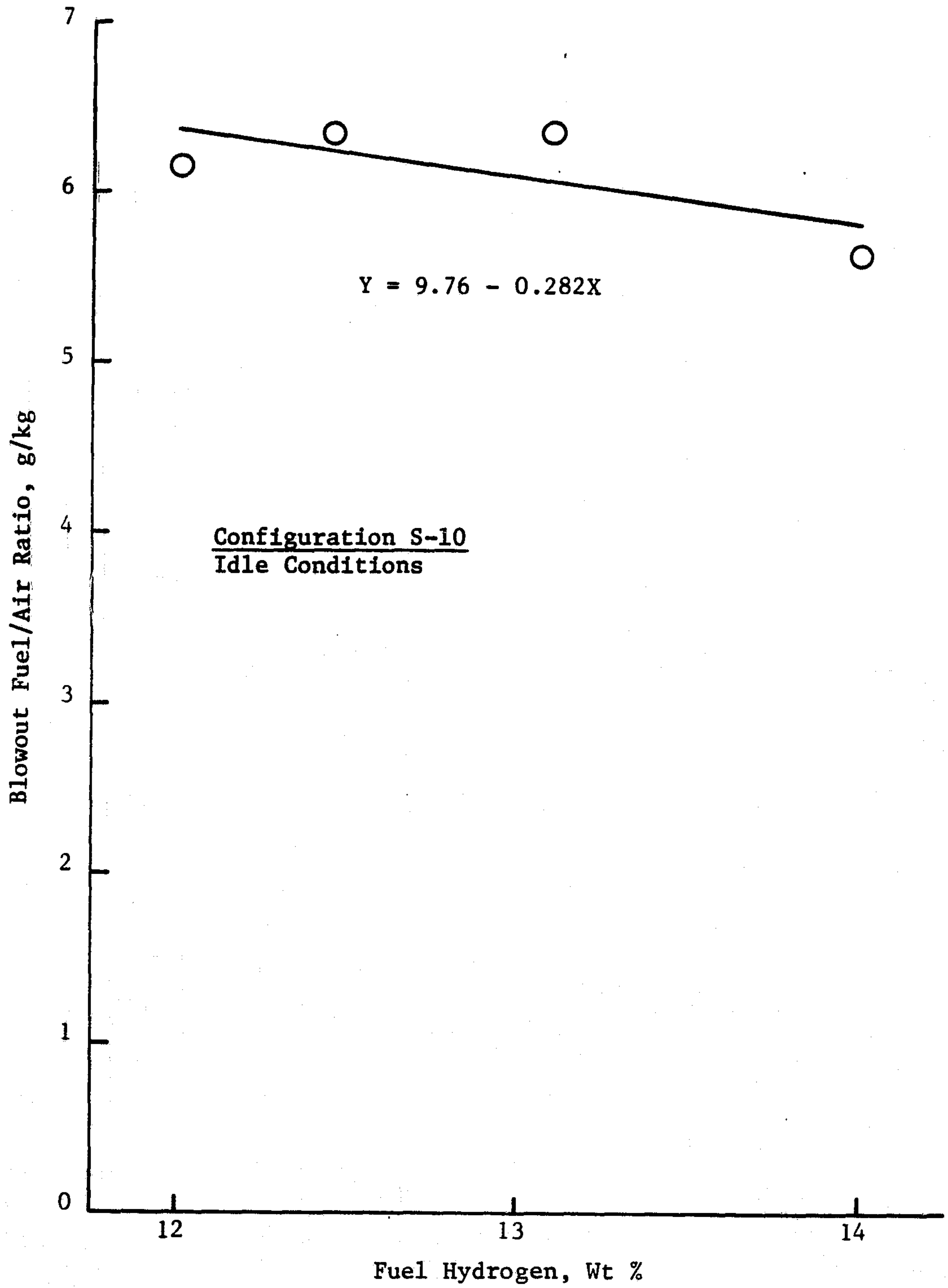

Figure 6-30. Effect of Fuel Hydrogen Content on Single-Annular Combustor Lean Blowout at Idle.

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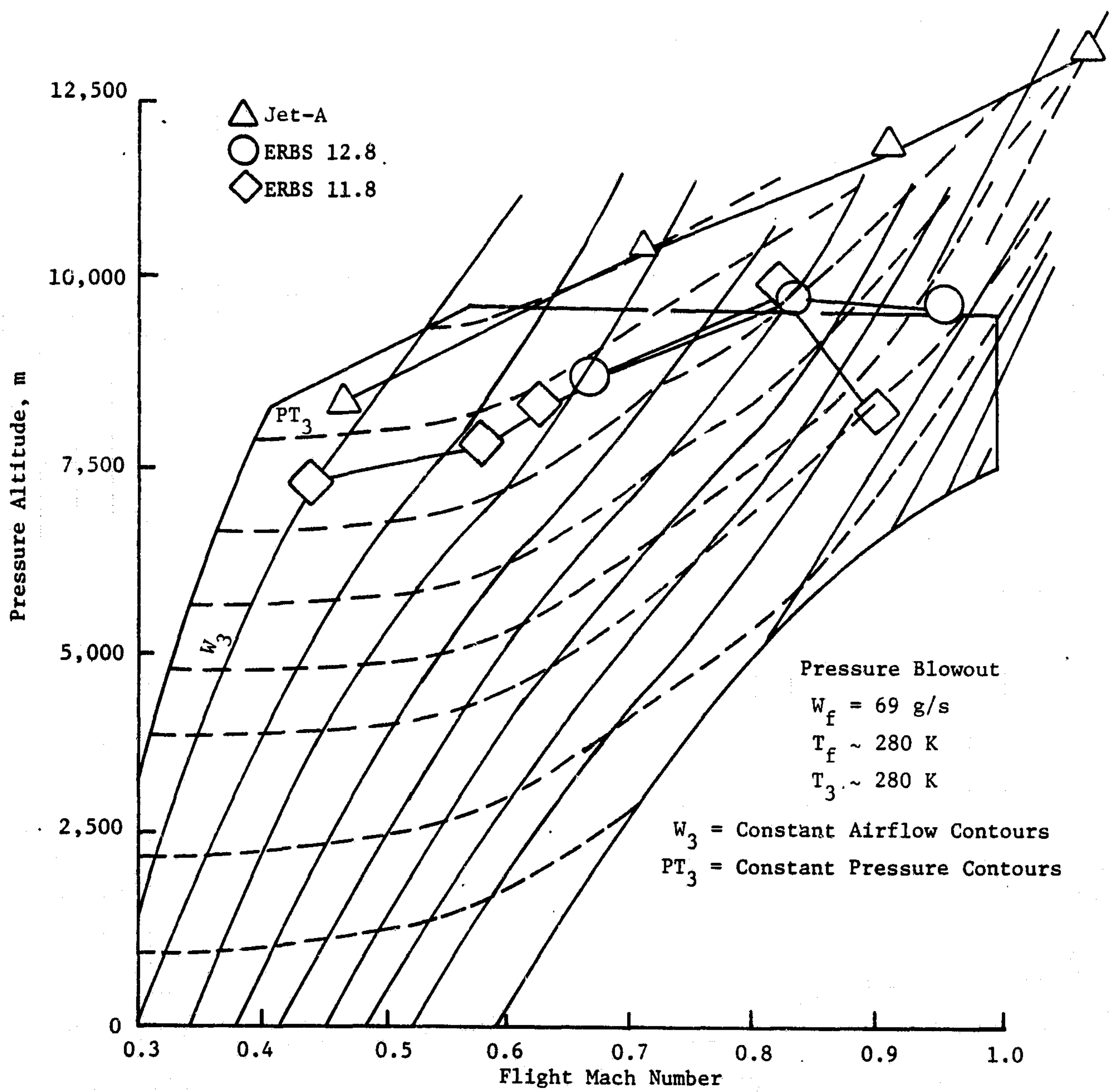


Figure 6-31. Effect of Fuel Type on Single-Annular Combustor Relight/Blowout.

and blowout have been related to fuel fluidity (viscosity and surface tension) and volatility. In fact, based on calculated relative drop sizes (a function of viscosity, surface tension, and density), blowout characteristics of all three ERBS fuels would be expected to be similar and slightly worse than Jet-A. This was the following result.

In summary, fuel effects were found to significantly affect combustor liner temperatures and altitude blowout performance. Trends observed in measured flame radiation and liner temperatures indicated performance degradation as fuel hydrogen content was decreased. Sensitivity to fuel hydrogen content was reduced at higher combustor inlet temperatures and pressures, which is consistent with observed smoke emissions trends. The use of smoke reduction techniques and thermal barrier coatings in the final single-annular combustor configuration nearly eliminated liner temperature sensitivity to fuel hydrogen and reduced liner temperatures to levels well below the baseline combustor, thereby increasing predicted combustor life. Altitude blowout capacility was also reduced with fuels having lower hydrogen contents. Improvement in single-annular combustor altitude blowout performance or measures to reduce sensitivity to fuel properties will be required to meet the program altitude relight/blowout goals with the heavier, lower hydrogen content fuels. No other aspects of combustor performance were significantly affected by changes in fuel hydrogen content.

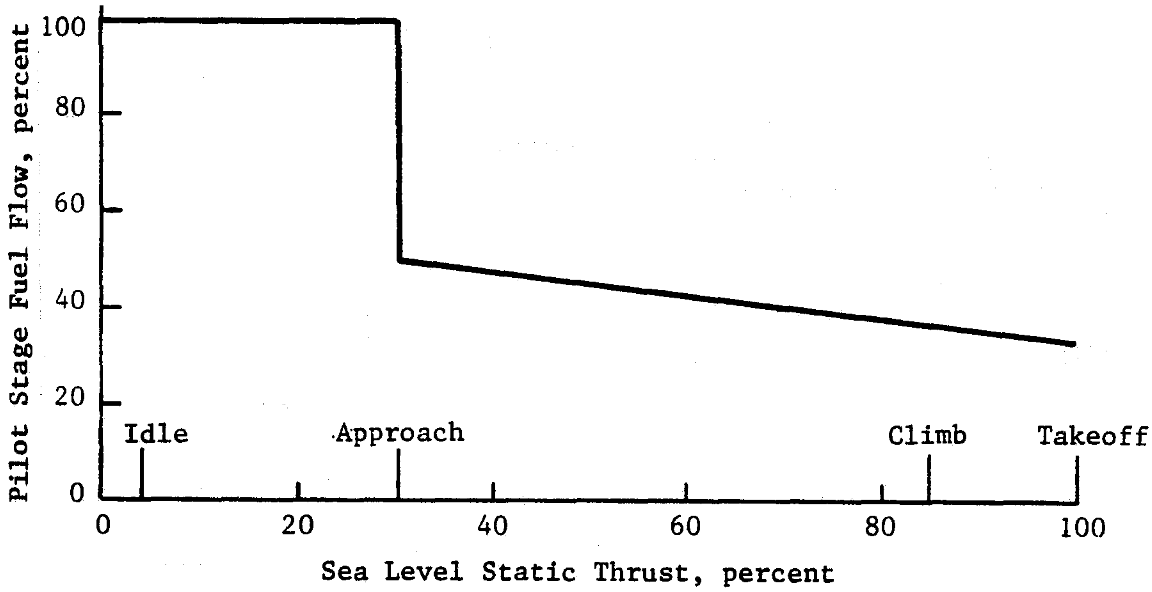
6.2 DOUBLE-ANNULAR COMBUSTOR

6.2.1 General Emissions and Performance Characteristics

In the discussions that follow, test data obtained with double-annular combustor Configurations D-5 and D-6 will be used to describe the emissions and performance characteristics of this combustor concept. These two configurations incorporated all the key design features identified during the test program and are, therefore, representative of the final state of development of this concept.

The only difference between Configurations D-5 and D-6 was in the size of the pilot stage fuel nozzles. Configuration D-5 used pilot stage fuel nozzles sized for high fuel injection pressure drop and, therefore, good atomization at idle operating conditions. However, the fuel flow required for operation at intermediate and high power levels could not be obtained with these nozzles due to fuel injection pressure limitations. Therefore, only idle data and a limited amount of data at simulated approach operating conditions were obtained with this configuration. Configuration D-6 used pilot stage fuel nozzles sized to provide the full flow required for operating at the true (full pressure) takeoff condition with acceptable fuel injection pressures (less than 7 MPa). With these nozzles, fuel injection pressure drop at idle was very low, less than about 0.15 MPa. In an actual application, dual orifice fuel nozzles would be used to provide the same pilot stage fuel flow characteristics as these two configurations.

The double-annular combustor is a two-stage system. It is therefore necessary to define a fuel flow schedule to distribute the fuel between the pilot and main stages. The nominal fuel flow schedule selected for this program is shown in Figure 6-32. On the sea level operating line, all of the fuel is supplied to the pilot stage up to the 30%, or approach, power level. At this condition, transition to two-stage burning is accomplished by supplying 50% of the total fuel to the main stage while simultaneously reducing the pilot stage fuel flow. The main stage is ignited by the pilot, with no auxiliary ignition device being required. Between 30% and 100% power, the proportion of fuel to the pilot stage is gradually reduced from 50% to about 33%. The 30% power level was selected for transition in this example in order to provide two-stage operation during the approach portion of the flight. This eliminates the requirement to ignite the main stage in the event that a sudden increase in power is required and avoids extended operation with unfueled nozzles at elevated inlet temperatures. However, engine test results with a double-annular combustion system, conducted during the NASA/GE Experimental Clean



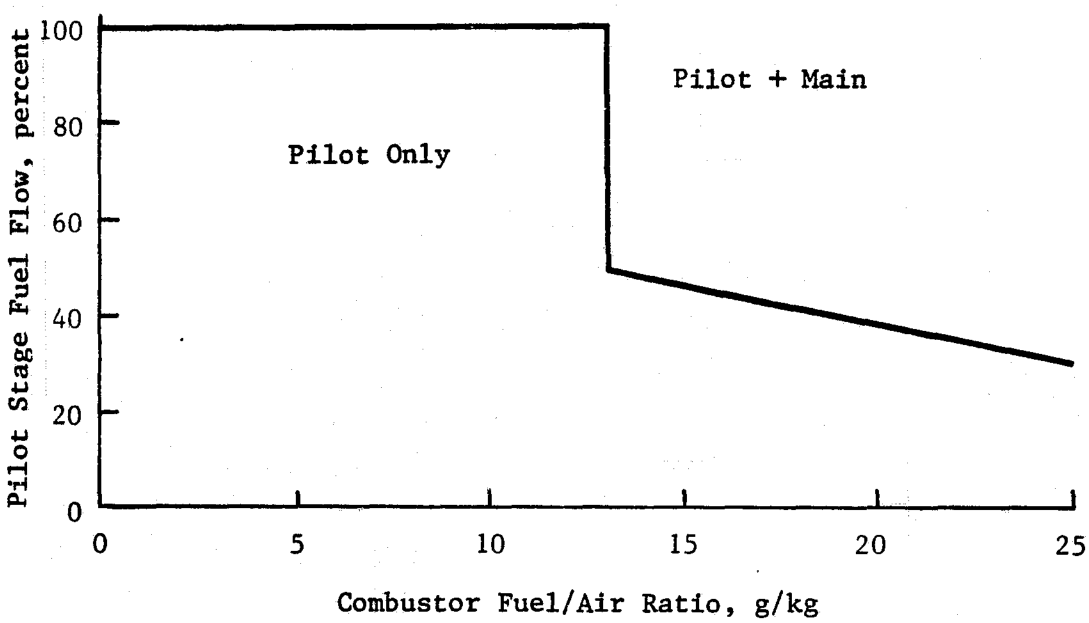


Figure 6-32. Double-Annular Combustor Fuel Flow Scheduling.

Combustor Program (ECCP), Reference 10, indicate that main stage ignition will not cause any significant delay in acceleration, so a higher power transition point could also be considered.

Although transition to two-stage operation was based on operation on the sea level operating line, the critical engine variable for fuel staging is combustor fuel/air ratio. The fuel flow schedule is also shown as a function of fuel/air ratio in Figure 6-32. Note that the cruise operating points all fall in the two-stage portion of this fuel schedule.

6.2.1.1 Emissions

Double-annular combustor carbon monoxide and unburned hydrocarbon emissions levels are shown over the combustor operating range in Figure 6-33. CO and HC both decrease repidly during pilot-only operating as power is increased from the idle conditions to the approach conditions. When the main stage is ignited, both the main and pilot stages are very fuel lean, and CO and HC emissions both increase substantially. As power is increased above the approach condition, the combustor fuel/air ratio increases, and CO and HC decrease rapidly.

During tests with Configuration D-5, a range of pilot to main stage fuel flow splits was evaluated to determine if CO and HC emissions could be reduced. As shown in Figure 6-34, no significant reduction in these emissions was obtained. A reduction in pilot stage flow resulted in an increase in CO emissions and a reduction in HC emissions. The same trend was observed in the NASA/GE ECCP (Reference 10). Main stage fuel staging was also evaluated. A staging configuration in which approximately one-half of the fuel is supplied to the pilot stage and the remainder is supplied to a 180° sector of the main stage was simulated by doubling the main stage fuel flow. With this configuration, CO is reduced by 90% and HC is reduced by 80%.

Double-annular combustor NO_x and smoke emissions over the operating range are shown in Figure 6-35. NO_x and smoke both increase

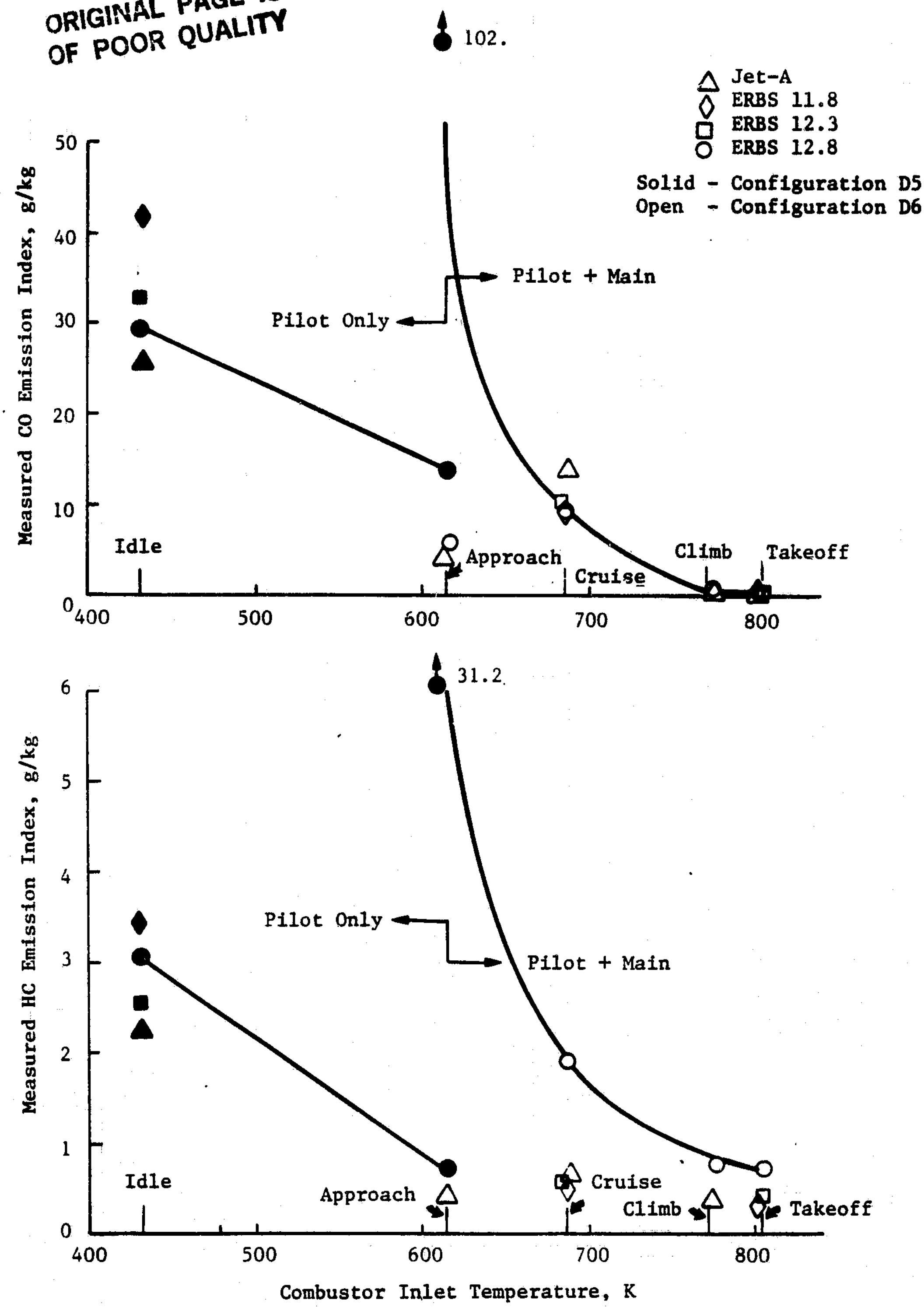
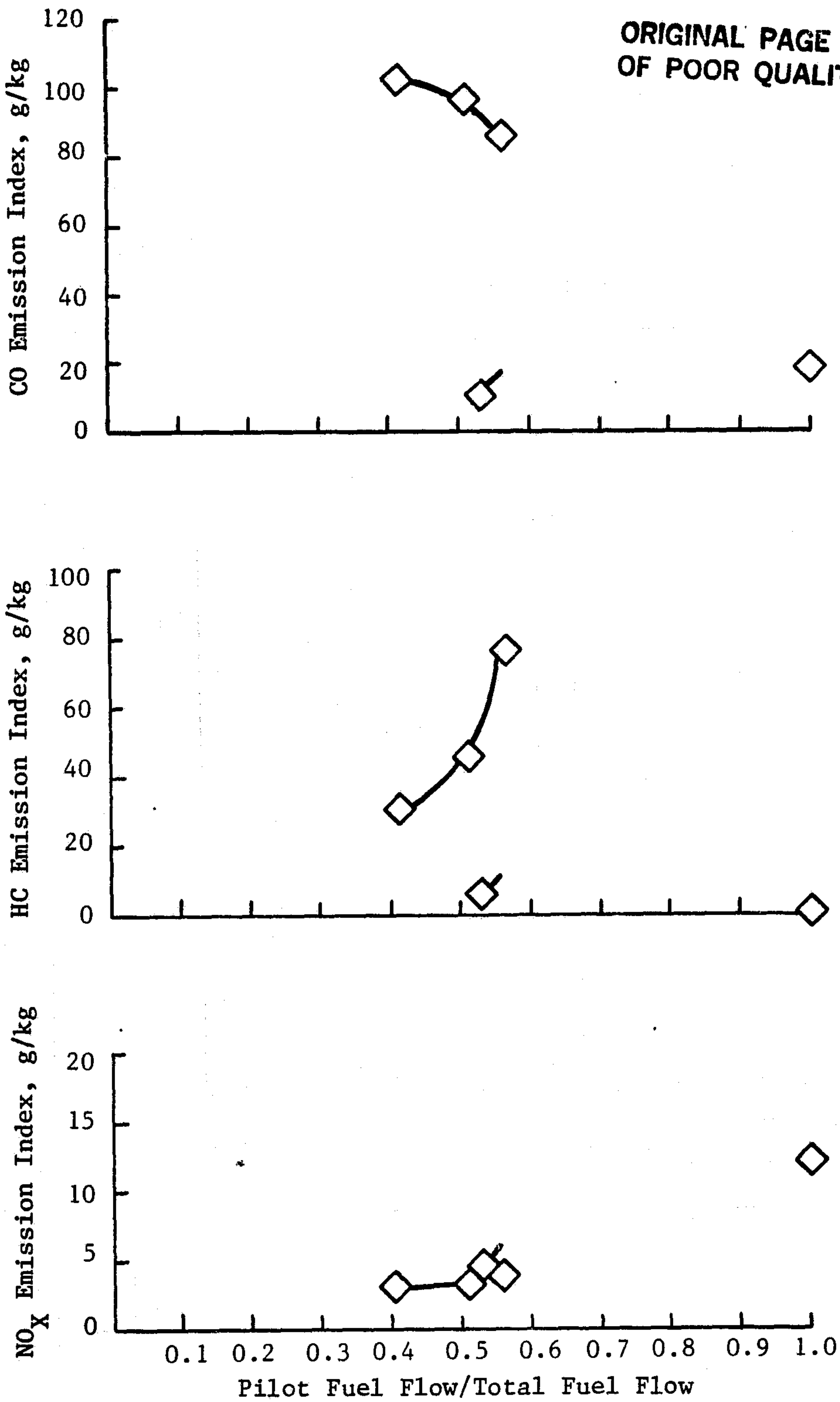


Figure 6-33. Double-Annular Combustor CO and HC Emissions.



Note: Flagged Symbols Indicate Main Stage Sector Burning.

Figure 6-34. Effect of Fuel Flow Distribution on Double-Annular Combustor Emissions at Approach Conditions.

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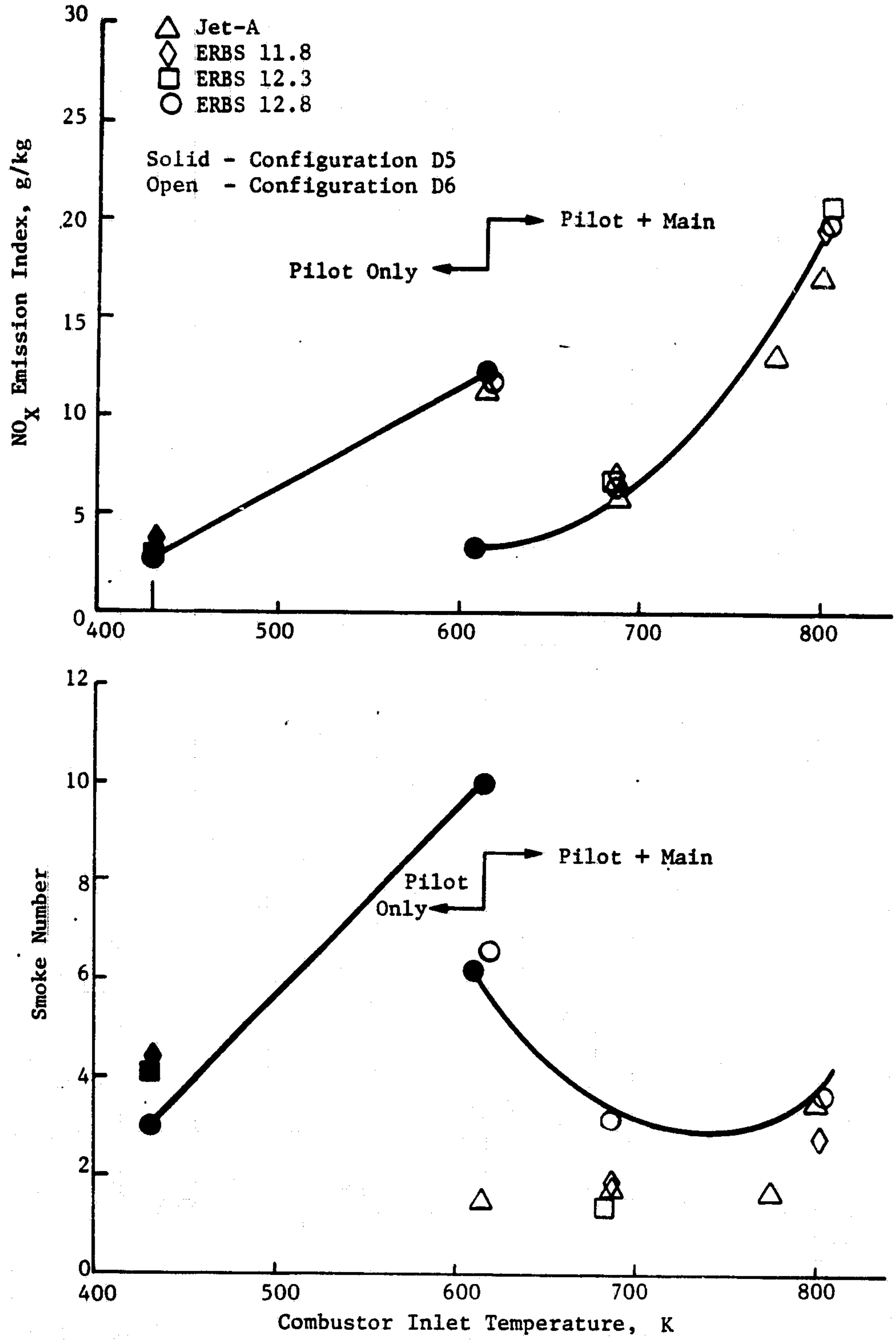

Figure 6-35. Double-Annular Combustor NO_X and Smoke Emissions.

rapidly as power is increased from idle to approach. Both of these emissions are then substantially reduced with transition to two-stage opera- tion. Above the approach power level, NO_x again increases rapidly, while smoke emissions remain at a fairly constant level.

During two-stage operation, NO_x was found to be quite sensitive to the fuel flow split between the pilot and main stages. This effect at approach conditions was shown in Figure 6-34. At higher power levels, NO_x emissions were increased by about 25% when the pilot stage fuel flow was increased from 33% to 42% of total fuel flow.

EPA parameter values for the double-annular combustor, using three different fuel staging modes at approach power, are presented in Table 6-2. Emission levels approached the program goals with pilot-only operation at the approach condition, and similar levels were obtained with main stage sector burning at these conditions. It is thought that all emission goals could be met with normal development using either of these two fuel staging modes. However, much higher CO and HC levels are obtained when two-stage operation without sector burning is employed at approach.

6.2.1.2 Performance

Average and maximum liner temperature differentials for the final double-annular combustor configurations are shown in Figure 6-36. Average temperature differential increases monotonically with increasing power level. At low power, with only the pilot stage in operation, maximum liner temperatures occur on the outer (pilot stage) liner. The highest liner temperature differentials were measured on the outer liner at the approach condition. However, the highest absolute temperatures were measured on the inner (main stage) liner at takeoff condition, where combustor inlet air temperature is also at its highest.

Detailed liner temperature at the takeoff operating conditions are presented for Configuration D-3 in Figure 6-37. This figure also shows the effects of variation in pilot-to-main-stage fuel flow split on local liner temperatures. At takeoff conditions, outer liner temperatures and centerbody temperatures were all well below the design goal. Inner liner temperatures were somewhat higher and were above the goal with 33% of the

Table 6-2. Double-Annular Combustor EPA Parameters.

Approach Power Operating Mode	EPA Parameter, g/kN		
	CO	HC	NO_x
Pilot Stage Only	35.9	6.1	35.2
Pilot and Main	92.2	22.3	29.7
Pilot and Main with Main Stage Sector Burning	38.6	7.9	30.6
Goal	25.0	3.3	33.0

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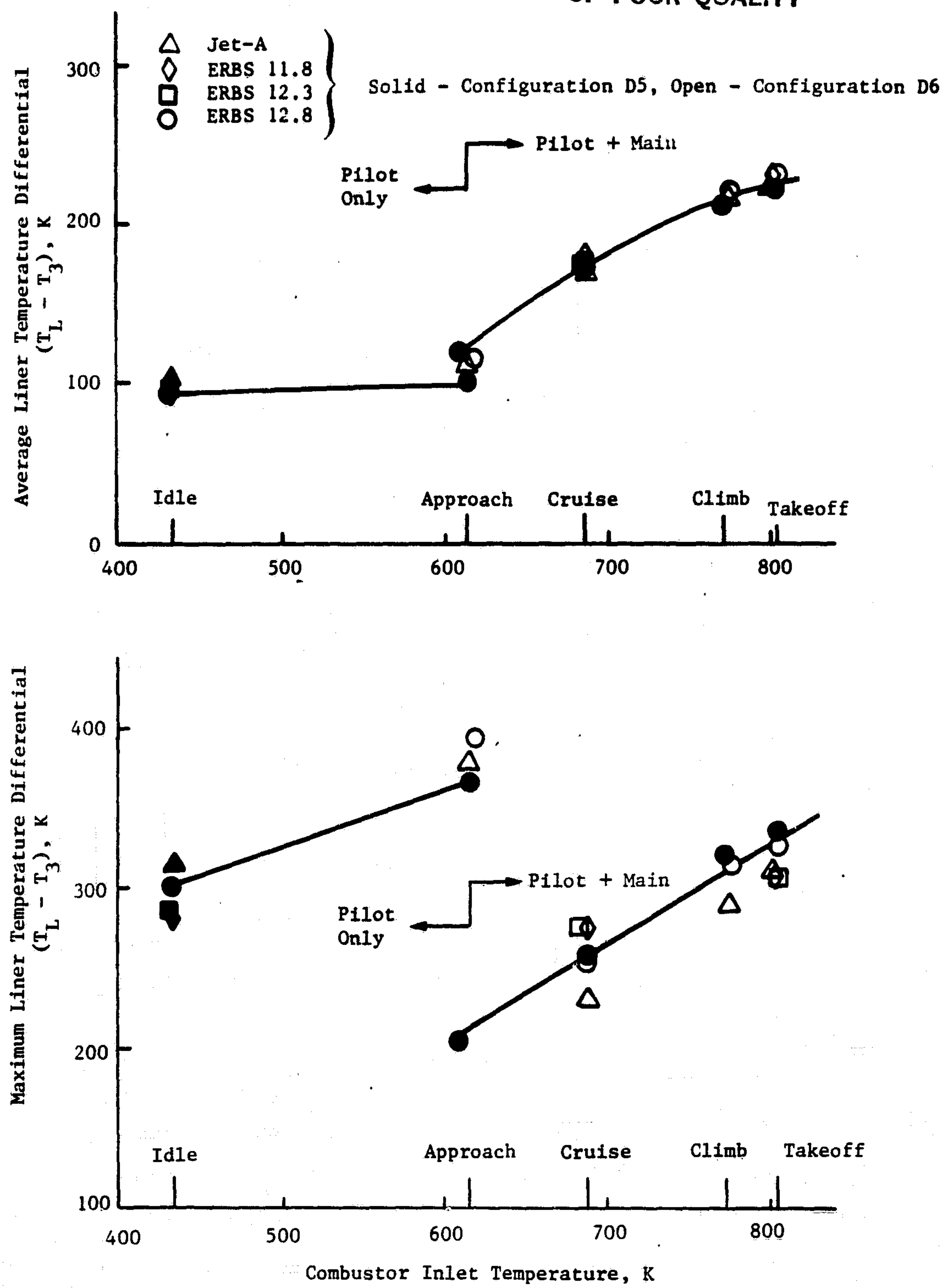

Figure 6-36. Double-Annular Combustor Average and Maximum Liner Temperature.

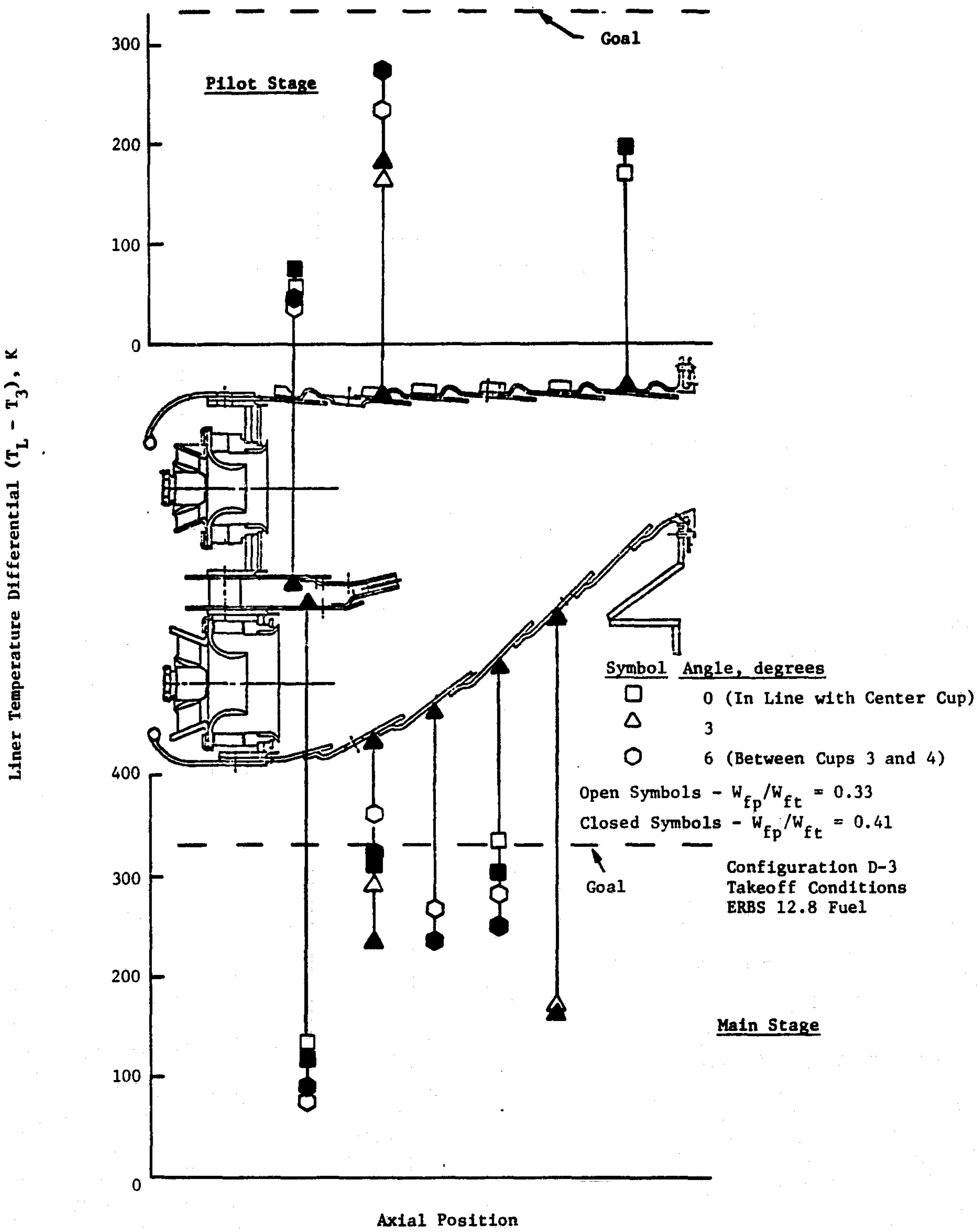

Figure 6-37. Detailed Double-Annular Combustor Liner Temperatures.

fuel supplied to the pilot stage. By increasing pilot stage fuel flow above 40% of the total, all main stage temperatures are reduced to levels below the goal. Although increased, pilot stage metal temperatures are still below the goal. In the final configuration of this concept, pilot stage fuel was reduced to 33% of the total at takeoff operating conditions to reduce NO_x emissions. Inner liner temperatures were reduced below the goal by using thermal barrier coatings.

The variation in measured radiant heat flux with power level is shown in Figure 6-38. The radiation measurement on the double-annular combustor was located in the pilot stage primary zone, so radiation levels were strongly influenced by the pilot dome fuel/air ratio. Radiation increases between idle and approach when only the pilot stage is operated. As fuel is transitioned to the main stage, the radiation level was reduced. The relationships between pilot dome fuel/air ratio, radiation and pilot stage primary zone metal temperatures is shown in Figure 6-39. Liner temperature differentials correlate with pilot stage fuel/air ratio over a wide range of operating conditions, whereas radiant heat flux tends to increase with both fuel/air ratio and combustor inlet temperature. Comparing the two curves, it is apparent that liner temperature differentials at the high power test points, where high radiant heat flux levels occurred, were increased slightly, but radiation effects were small. This implies that convection heat transfer is controlling in the pilot stage and that fuel properties which influence only flame radiation will not strongly effect pilot stage liner temperatures.

Double-annular combustor exit temperature profiles, computed from a combination of individual gas samples and thermocouple measurements obtained at takeoff operating conditions, are shown in Figure 6-40. Configuration D-4, with 33% of the fuel flow to the pilot stage, provided very low pattern and profile factors. This configuration met the pattern and profile factor goals of 0.25 and 0.11, respectively. However, both the peak and average temperature profiles were somewhat inboard peaked with the relatively low pilot stage fuel flow which was selected for reduced NO_x emission. Configuration D-3, which was run with 41% of the total

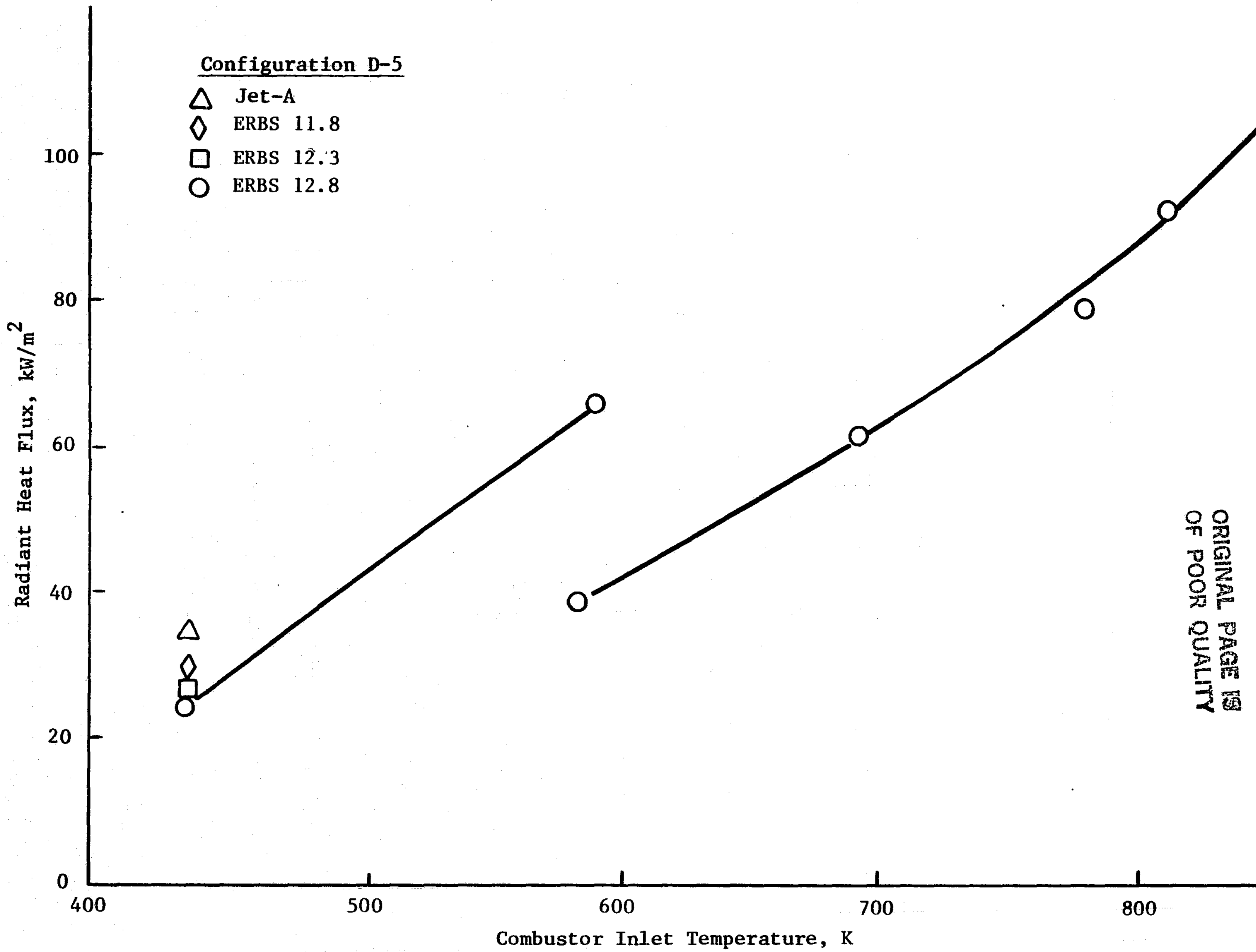

Figure 6-38. Double-Annular Combustor Pilot Stage Radiant Heat Flux.

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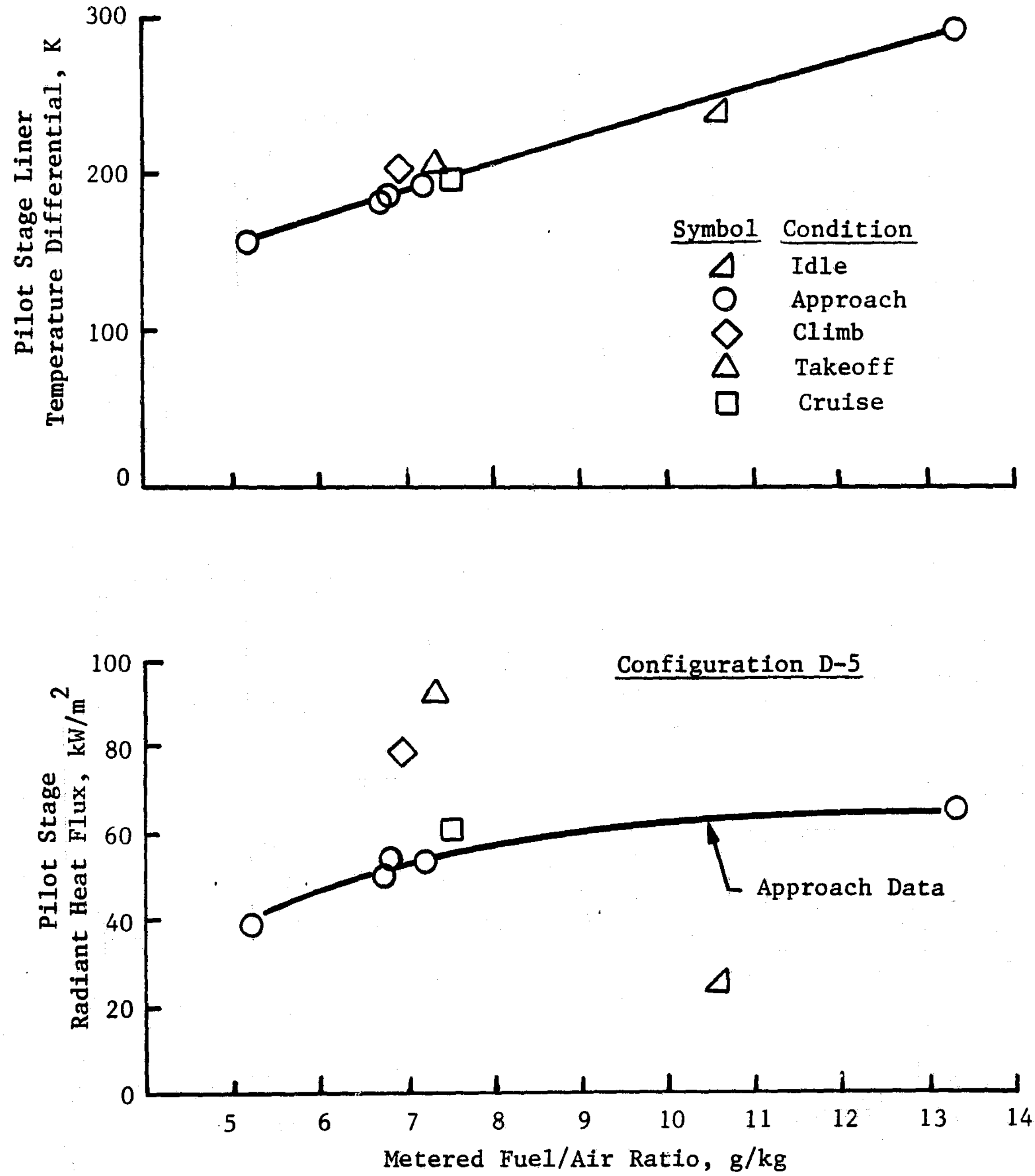

Figure 6-39. Effect of Pilot Stage Fuel/Air Ratio on Double-Annular Combustor Liner Temperature and Flame Radiation.

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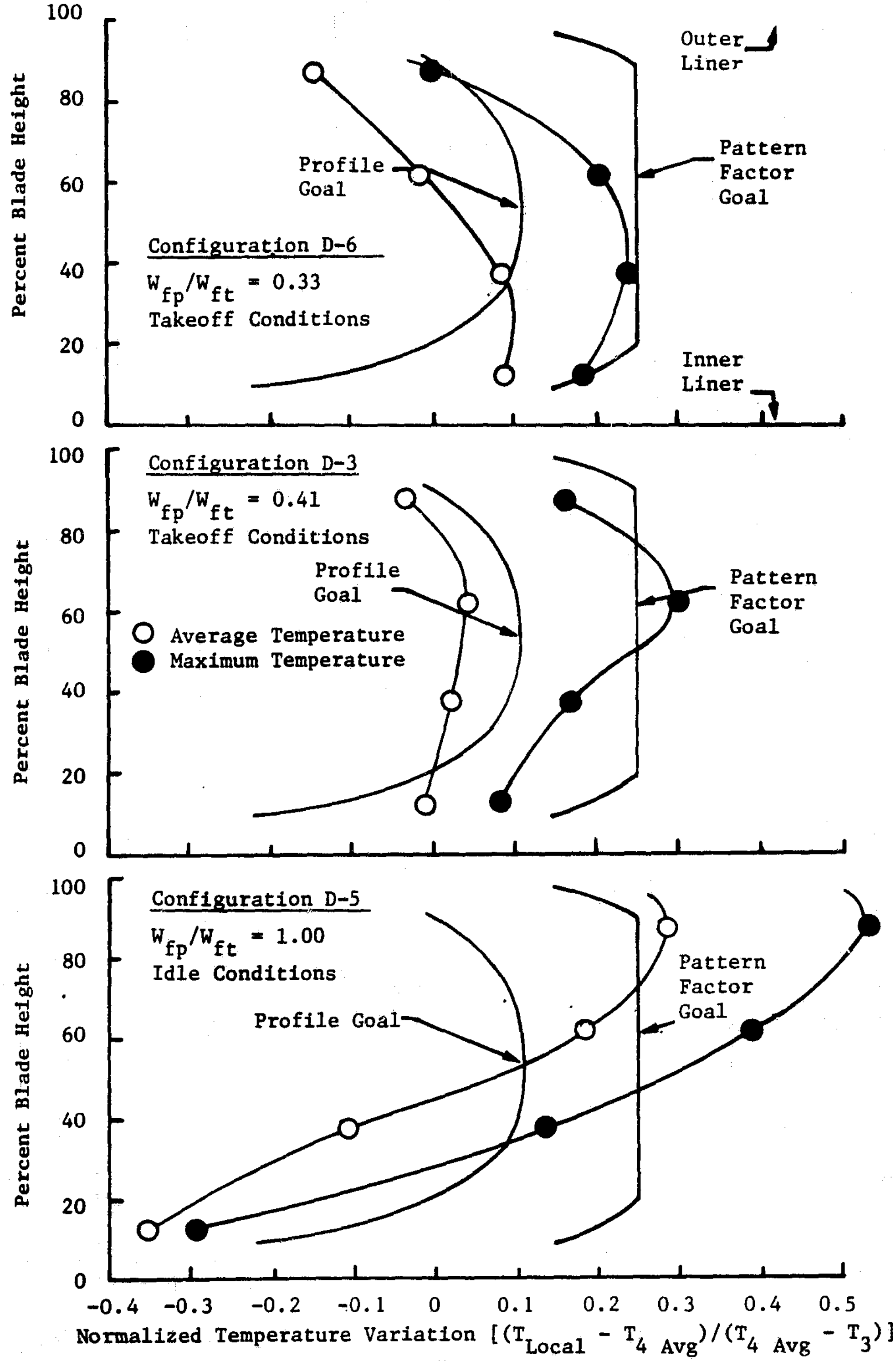


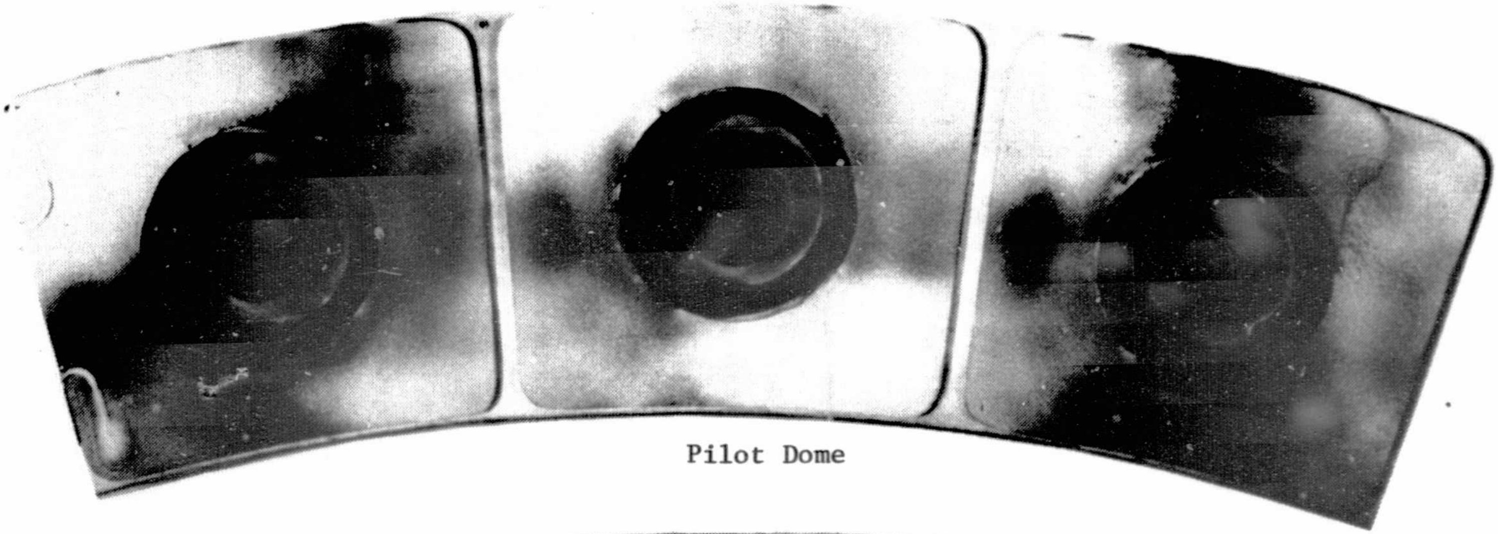
Figure 6-40. Double-Annular Combustor Exit Temperature Profiles.

fuel flow to the pilot stage, produced a more desirable outboard peaked profile, although the pattern factor was slightly above the goal. Thus with the double-annular combustor concept, it is possible to adjust the exit profiles by varying the fuel flow split. When pilot-only operation is employed, as at idle conditions, the temperature profiles become very outboard peaked.

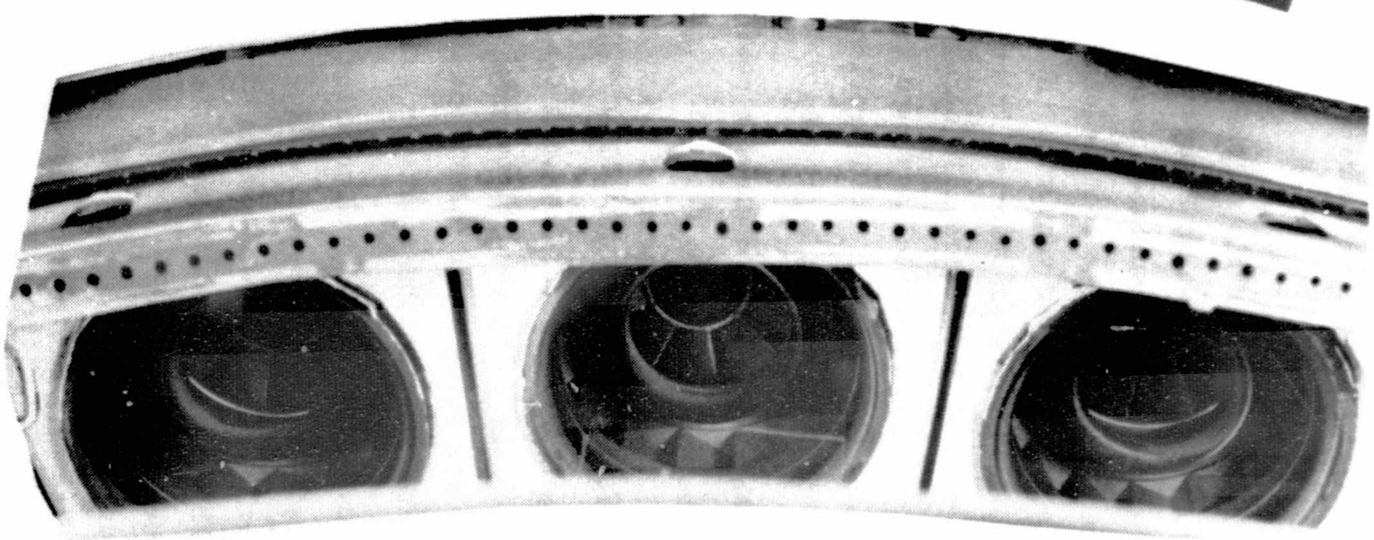
Postrun photographs of the pilot and main stage swirlers of Configuration D-6 are shown in Figure 6-41. The main stage swirlers and thermal barrier coated dome surfaces were carbon-free. The pilot dome was discolored and a moderate coating of carbon was evident on the inner surface of the pilot swirler venturis. Moderate carboning of the pilot stage fuel nozzle tips was also observed in this configuration. However, the pilot stage venturi and fuel nozzle carboning occurred only when the unshrouded pilot stage fuel nozzle tips were used. In the main stage, and in the pilot stage of earlier configurations which used the shrouded fuel nozzle tip, carboning was not a problem.

Other aspects of combustor performance met the design goals. Combustion system pressure drop, corrected to the design condition, averaged about 5.2% for Configuration D-6. Pilot stage blowout at idle occurred at a fuel/air ratio of about 5 g/kg, well below the goal of 7.5 g/kg. Combustor efficiency was above 99% except during two-stage operation at the approach operating conditions. As shown in Figure 6-42, combustion efficiency was below about 95% except when main stage sector burning was simulated or when the combustor was operated on the pilot stage alone.

Overall, double-annular emissions and performance are characterized by trade-offs which depend on fuel staging between the pilot and main stages. At high power levels, very uniform exit temperature profiles can be achieved, and the shape of the exit profile, the relative temperatures of the inner and outer liners, and NO_x emissions can be controlled by varying the fuel distribution. However, exit temperature profile and liner temperature performance is best with a larger proportion of the flow to the pilot stage, while NO_x emissions are reduced as main stage flow



Pilot Dome



Main Dome

Figure 6-41. Post Run Photograph of Double-Annular Combustor Domes.

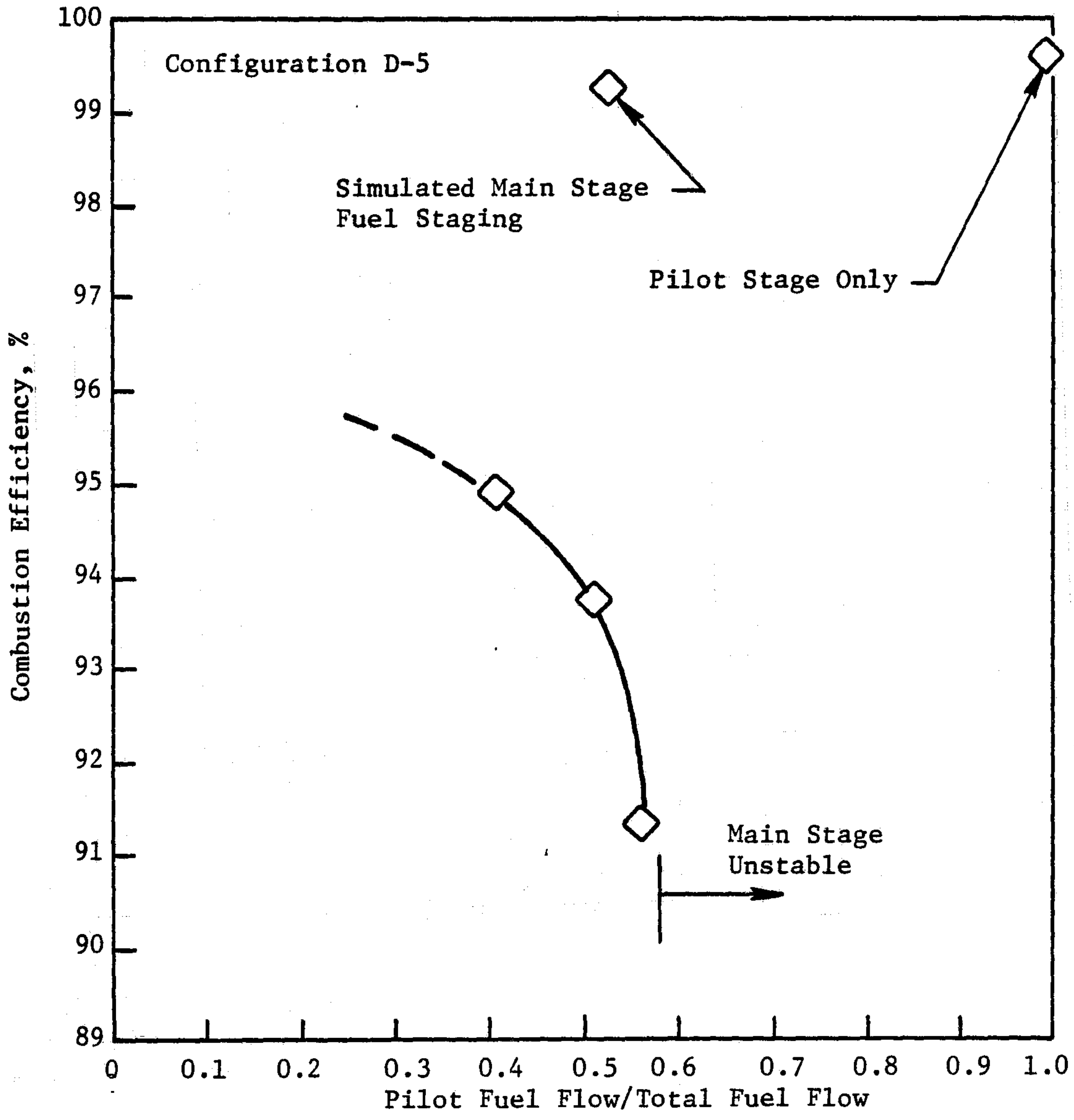


Figure 6-42. Effect of Fuel Flow Splits on Combustion Efficiency at Approach Operating Conditions.

is increased. At intermediate power levels, combustor performance, durability, reliability, emissions, and control complexity can all depend on the method used to transition from one-stage to two-stage burning. Transition to uniform two-stage operation at or below the approach power level would be desirable in terms of durability and reliability, since the exposure of unfueled fuel nozzles to high inlet temperatures would be reduced, the need to crossfire the main stage during a rapid acceleration would be eliminated, and the extremely outboard peaked exit temperature profile characteristic of single-stage burning would be limited to low power operation. On the other hand, the combustion efficiency and CO and HC emissions goals are far more likely to be met with transition to two-stage operation at power levels above approach. A third alternative, sector burning of the main stage during intermediate power operation, provides potential for high combustion efficiency and low CO and HC emissions and eliminates the main stage crossfire requirments during acceleration from the approach condition; but control complexity would be increased and problems of nonuniform exit temperature profiles and unfueled fuel injectors at intermediate power would persist.

6.2.2 Combustor Development Progress

The baseline double-annular test results indicated that the primary double-annular combustor development needs were improved combustion efficiency, or CO and HC emissions reduction at idle, and improved combustion efficiency during two-stage operation at intermediate power. Therefore, a majority of the modifications to this concept, which have been described in Section 4.2.2, were directed toward increasing combustion efficiency.

6.2.2.1 Emissions

Emission results obtained with the different double-annular combustor configurations are summarized in Figure 6-43. All of these values were calculated based on pilot-stage-only operation at the approach power level. As illustrated in Table 6-2, much higher CO and HC EPA parameters were obtained with two-stage operation at approach. Except as noted, calculated emissions were based on an idle setting of 4% of rated thrust. This is typical of actual CF6-80A graund idle operation.

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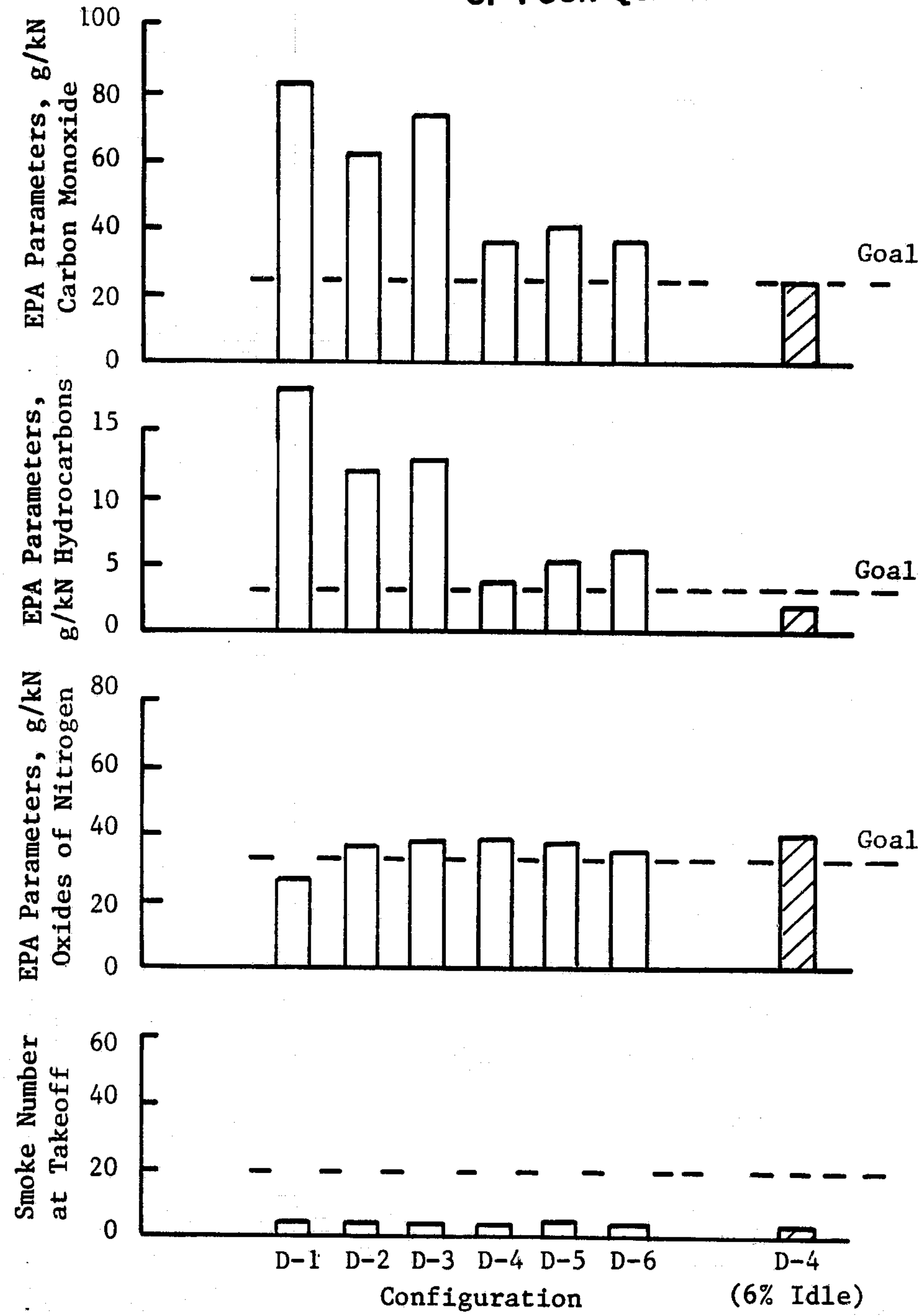

Figure 6-43. Double-Annular Combustor Emissions.

Good progress was made in reducing CO and HC levels. Over the course of the program, double-annular combustor CO levels were reduced by 57%, and HC levels were reduced by 66%. The configuration providing the lowest CO and HC levels was D-4. With that configuration, an additional 6% reduction in HC and a 30% reduction in CO are needed to meet the program goal when the 4% idle point is used. As indicated on the right of this figure, the CO and HC goals are actually met with this configuration, assuming that a 6% idle point is used. However, 6% thrust is higher than the current ground idle thrust specification.

The key modification for CO and HC emissions reduction was the use of the development type fuel nozzle tips to provide improved atomization at idle conditions. The idle emissions characteristics of the six double-annular combustor configurations, shown in Figure 6-44, illustrate this effect. Throughout the tests, the minimum CO levels occurred near the design fuel/air ratio, indicating that the selected pilot stage airflow distributions provided the proper stoichiometry for operation at this point. The configurations which incorporated the development type fuel nozzle tips all had reduced CO and HC levels. Changes in the pilot dome and liner cooling levels, the pilot swirler configuration, and pilot stage primary dilution all had relatively minor effects on idle emissions.

NO_x emission levels were below the program goal with the baseline configuration and tended to increase as CO and HC were reduced. Since NO_x levels were close to the program goal throughout the double-annular test series, no major effort was made to reduce this pollutant. In fact, it is significant to note that the increased main stage stoichiometry used in D-3 and subsequent configurations did not substantially increase NO_x emissions. NO_x levels for the final double-annular combustor configuration were only about 7% above the program goal.

Smoke levels with all of the double-annular combustor configurations were well below the program goal.

Based on the double-annular tests conducted in this program, it is thought that this combustor concept is capable of meeting all of the program emission goals, if the pilot stage is used for operation at approach

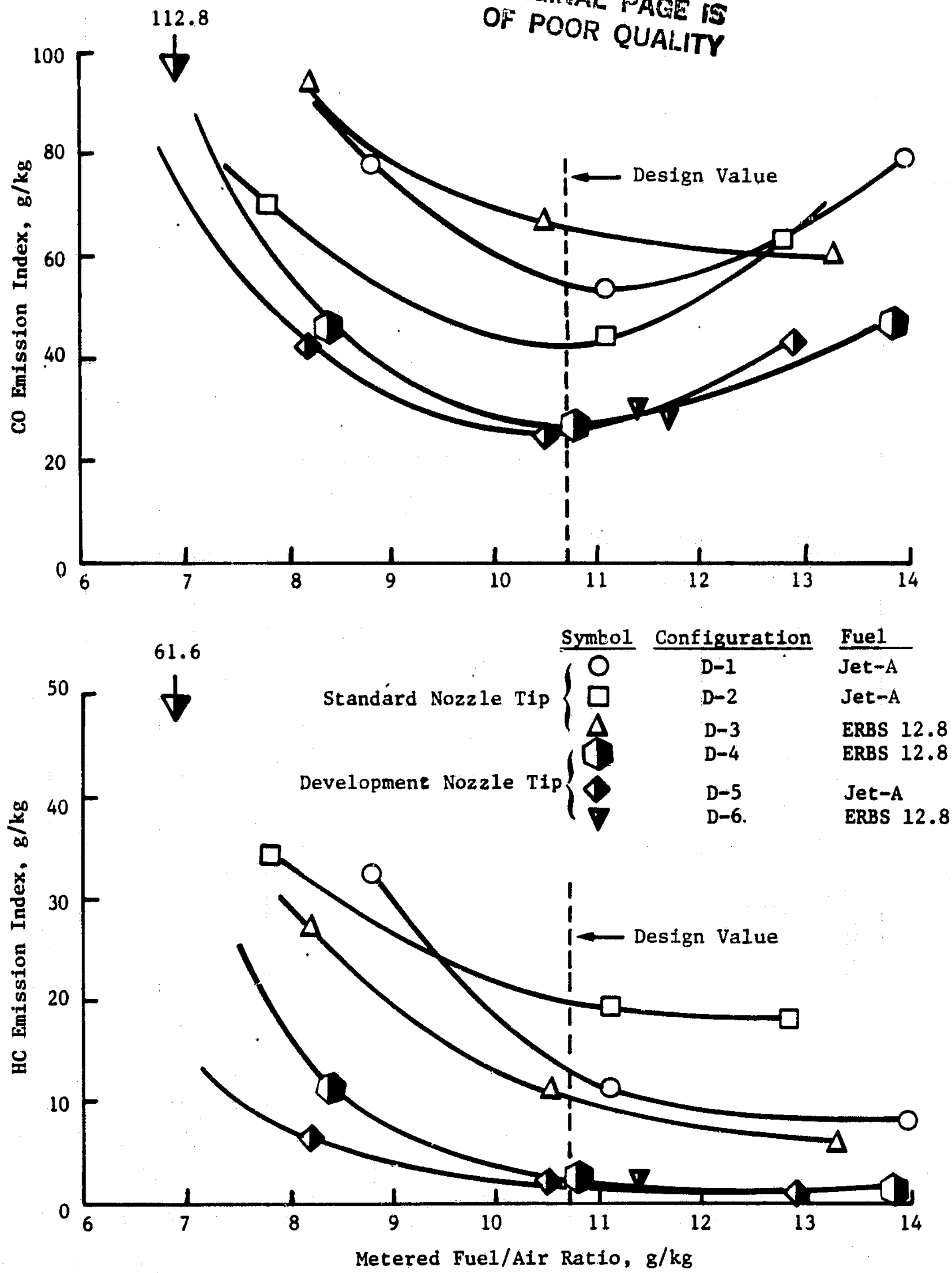

Figure 6-44. Double-Annular Combustor Idle Emissions.

conditions. Some additional pilot stage fuel injector, swirl cup, and dilution development would be required to meet the CO and HC goals, while refinement of the fuel staging schedules and additional main stage dilution development would be needed to meet the NO_x goal.

6.2.2.2 Performance

Double-annular combustor performance progress is summarized in Figure 6-45. Combustor liner temperatures and exit temperature profiles were both improved during the course of the test program. Combustion efficiency was also improved at the idle and approach operating conditions.

The primary modification for liner temperature reduction was the use of thermal barrier coatings to reduce inner liner temperatures. Average inner liner temperatures were reduced by about 30 K by using the thermal barrier coating. This offset the increase in inner liner temperature which resulted from the use of increased main stage fuel flow for NO_x reduction. Maximum liner temperatures were below the program goal with the final double-annular combustor configuration.

Fuel/air ratios for blowout at the idle operating conditions were well below the goal for all of the double-annular combustor configurations.

Exit temperature profile and pattern factors were reduced with the use of the richer main stage, in which the proportion of pilot stage fuel flow was increased at high power and which incorporated increased inner liner profile trim. Both of these features tended to reduce the inboard peaked temperature profiles. Profiles and pattern factors essentially met the program goals, except that the profile was still somewhat inboard peaked.

Combustion efficiency levels at the idle and approach operating conditions are summarized in Table 6-3. Idle combustor efficiency was above the goal of 99% in all configurations using the development type pilot stage fuel nozzles. Combustion efficiency during two-stage operation at approach was in the 95% to 96% range for concepts incorporating the richer main stage airflow distribution, compared to about 91% for the

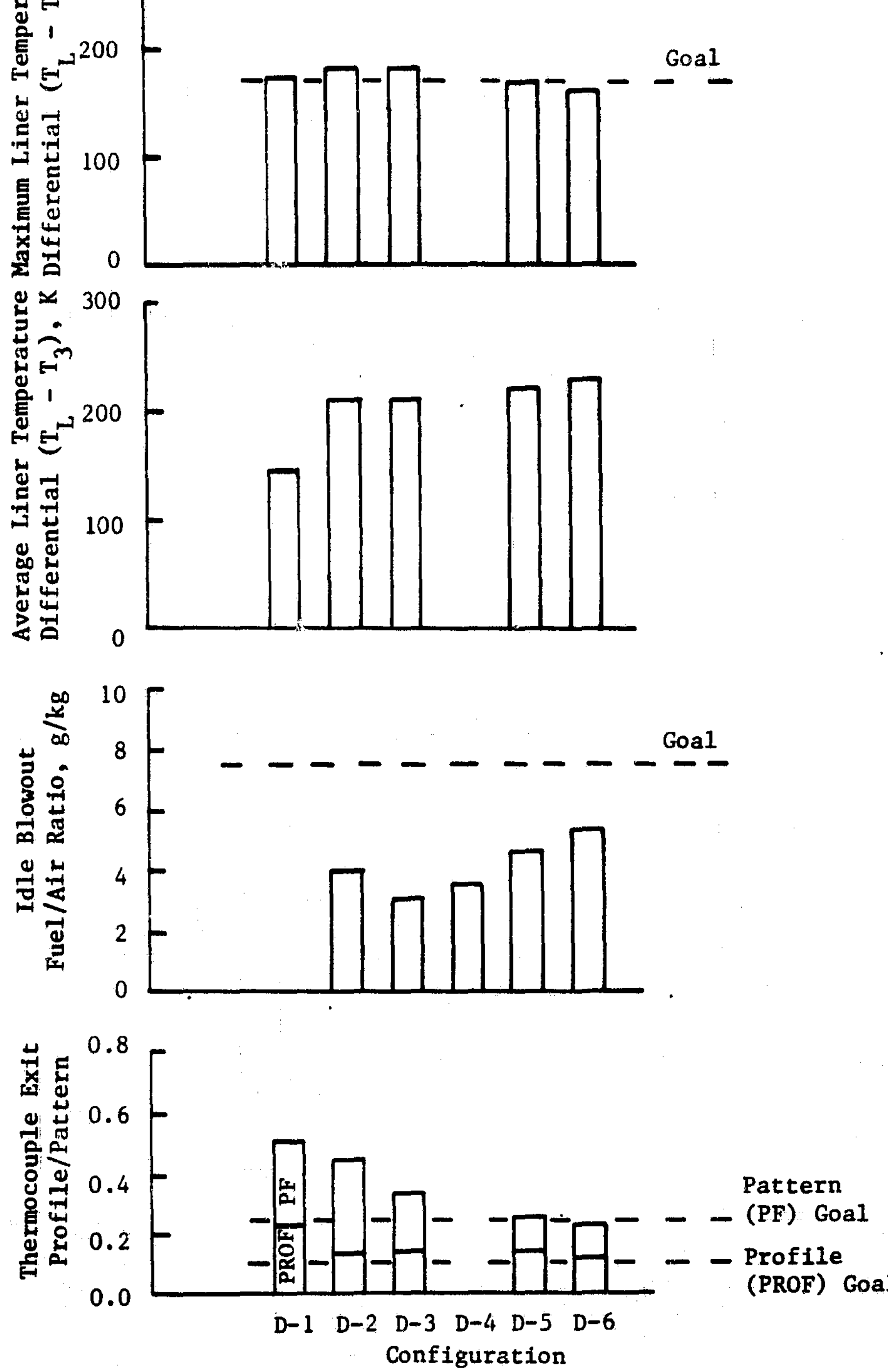

Figure 6-45. Double-Annular Combustor Performance.

Table 6-3. Double-Annular Combustor Combustion Efficiency

Configuration	Combustion Efficiency		
	Idle	Approach (Pilot Only)	Approach (Two Stage)
D-1	97.1	99.6	-
D-2	97.8	99.6	90.8 [1]
D-3	97.5	99.7	95.1 [2]
D-4	99.2 [3]	-	96.3 [2]
D-5	99.0 [3]	99.5	94.9 [2] (99.2 [4])
D-6	98.9 [3]	99.6	-

1 - Jet-A Fuel

2 - Rich Main Stage

3 - Development Type Pilot Stage Full Nozzle

4 - Main Stage Sector Burning Simulation

baseline flow distribution. The combustion efficiency goal was met with two-stage operation at approach only when main stage sector burning was simulated.

Combustor pressure drop for all of the double-annular combustor configurations was within one-half point of the design goal of 4.7%, and below the program goal of 6% at all operating conditions.

Combustor carboning occurred on the pilot stage fuel nozzle tips and primary swirler venturis of the configurations using the development type fuel nozzles.

In summary, during this Phase I program, the double-annular combustor was developed to the pilot where it met all of the performance goals except for carboning, if main stage sector burning is used at the approach condition. It is thought that the observed carboning could be eliminated without losing the benefits of the development-type fuel nozzle by the use of an air shroud on the pilot stage fuel nozzle tip. Altitude relight characteristics were not evaluated with the double-annular combustor concept, but the pilot stage should provide very favorable ignition behavior.

6.2.3 Fuel Effects

Three of the six double-annular combustor configurations were evaluated on two or more of the test fuels, and Configurations D-2 and D-6 were evaluated with all four fuels. Fuel effects on double-annular combustor emissions and performance, based primarily on these two combustor configurations, are discussed in the following paragraphs.

6.2.3.1 Emissions

Carbon monoxide emissions indices measured at the idle, cruise, and takeoff conditions with combustor Configurations D-2 and D-5/D-6 are shown in Figure 6-46. Levels measured with the final configurations are lower at all conditions that with Configuration D-2. Generally, CO tended to increase as fuel hydrogen content was reduced. At idle conditions, which largely determines the CO EPA parameter, CO emissions were increased by

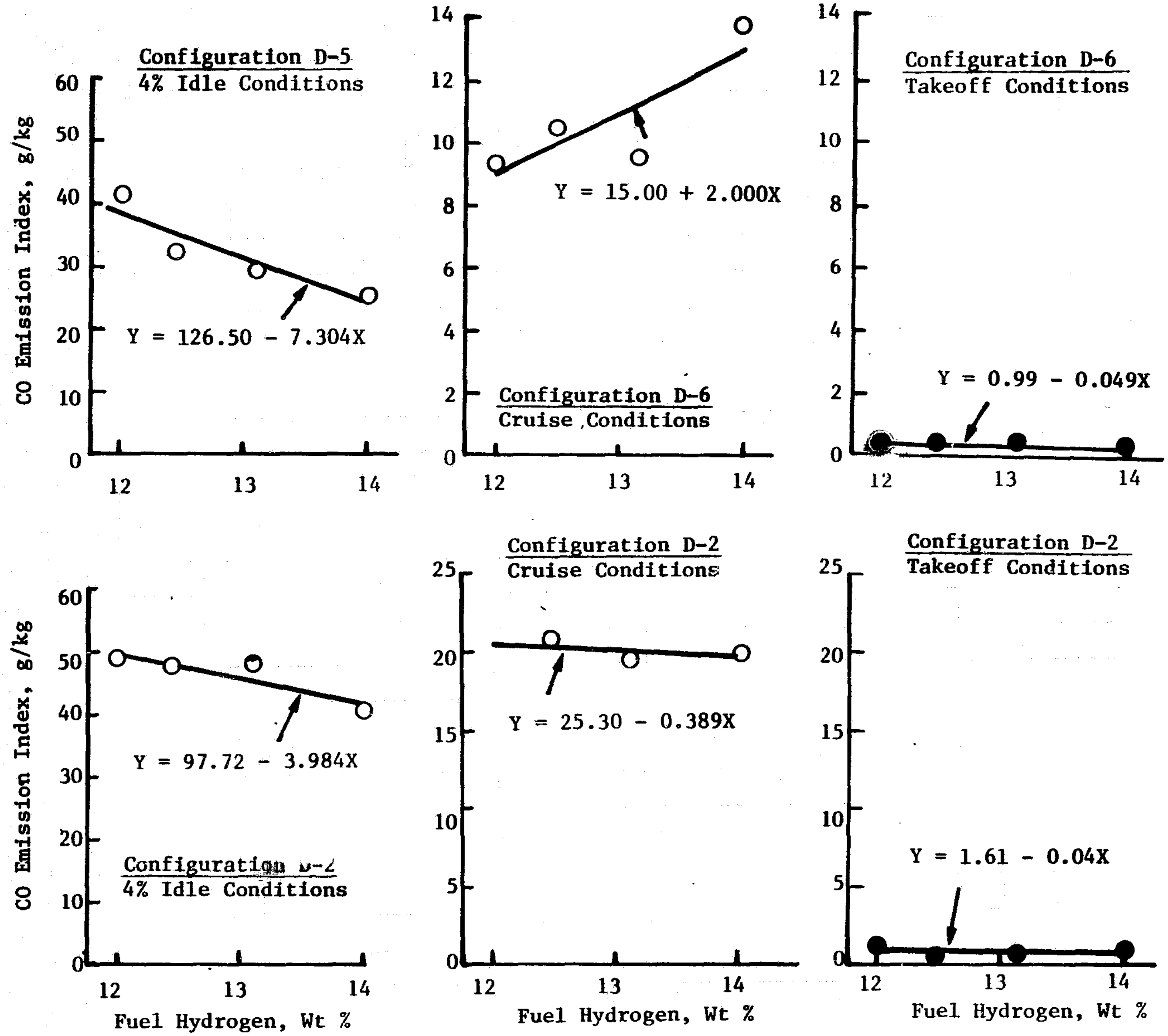

Figure 6-46. Effect of Fuel Hydrogen Content on Double-Annular Combustor Carbon Monoxide Emissions.

10% in Configuration D-2 and 30% in Configuration D-5 for a reduction from 14% to 13% fuel hydrogen, based on the best fit curve of CO as a function of fuel hydrogen content.

Emission indices for unburned hydrocarbons are shown as a function of fuel hydrogen content in Figure 6-47. At the idle condition, HC levels were significantly reduced in the final double-annular combustor configurations, relative to Configuration D-2. No clear trend in HC emissions was observed with variation in fuel properties.

The effect of fuel hydrogen content on NO_x emissions from the double-annular combustor is shown in Figure 6-48. Measured NO_x levels are similar for the two combustor configurations, and levels increase with decreasing fuel hydrogen content in all cases. At the takeoff operating condition, a reduction from 14% to 13% fuel hydrogen content resulted in an increase in NO_x of 12% with Configuration D-2 and 8% with Configuration D-6, based on best fit curves of NO_x emissions index as a function of fuel hydrogen content.

Double-annular combustor smoke emissions are shown as a function of fuel hydrogen content in Figure 6-49. Measured smoke levels were somewhat lower in Configurations D-5 and D-6 than in the baseline configuration. For both configurations, smoke levels increased very rapidly as fuel hydrogen content was reduced during pilot-stage-only operation at the idle conditions. Idle smoke levels were more than doubled over the range of fuels used. For two-stage operation at higher power levels, where smoke emissions are normally most critical, smoke levels were very low and were insensitive to fuel hydrogen content.

Measured emission levels and calculated EPA parameters for the final double-annular combustor configuration, when operated on Jet-A and ERBS 12.8 fuels, are compared in Table 6-4. All emission levels were lower with the Jet-A fuel, and the emissions reduction was sufficient to meet the NO_x goal with this fuel. The HC goal was also met with Jet-A, but this apparent HC reduction is thought to be due in part to data scatter not related to variation in fuel properties.

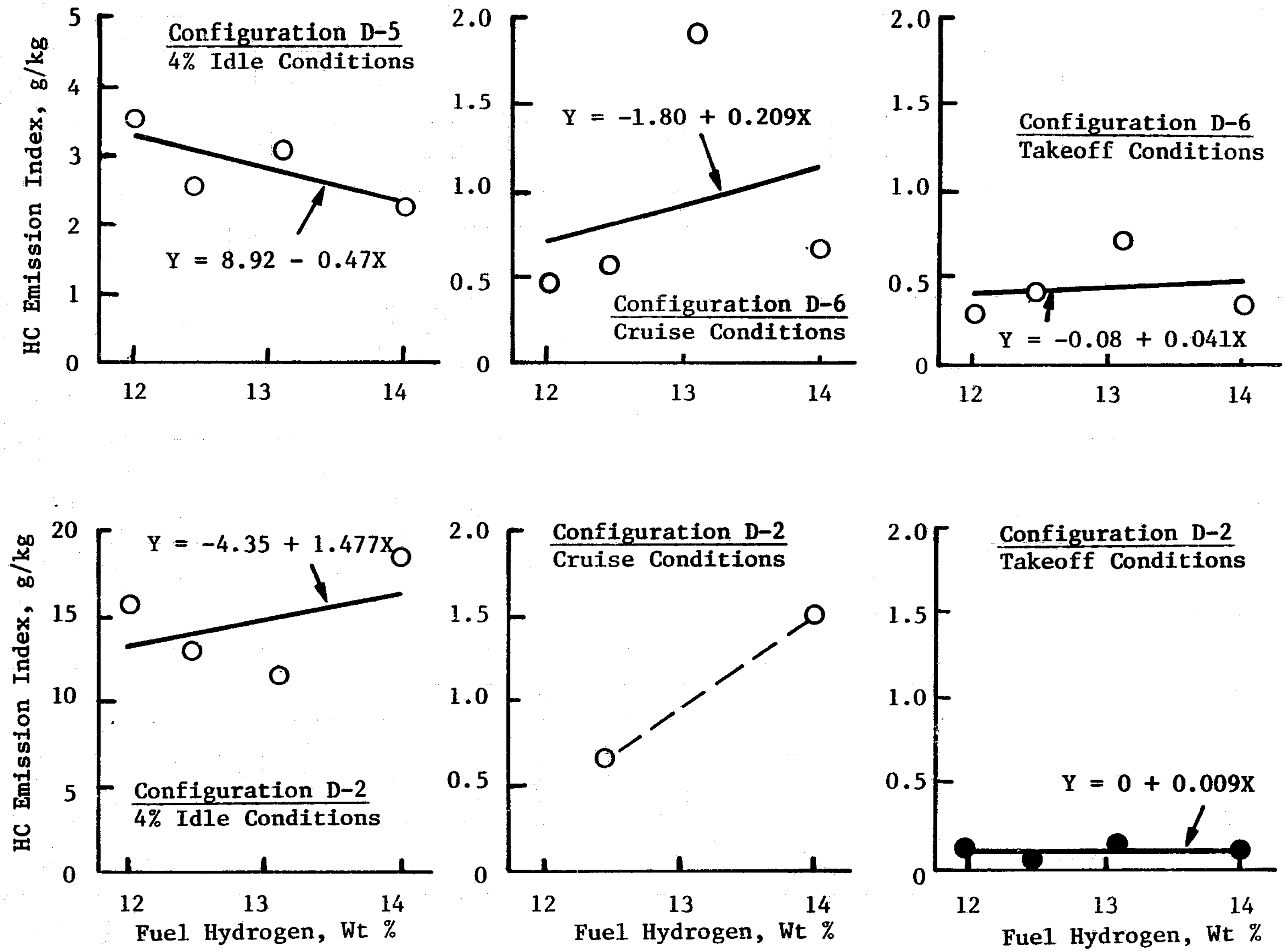

Figure 6-47. Effect of Fuel Hydrogen Content on Double-Annular Combustor Unburned Hydrocarbon Emissions.

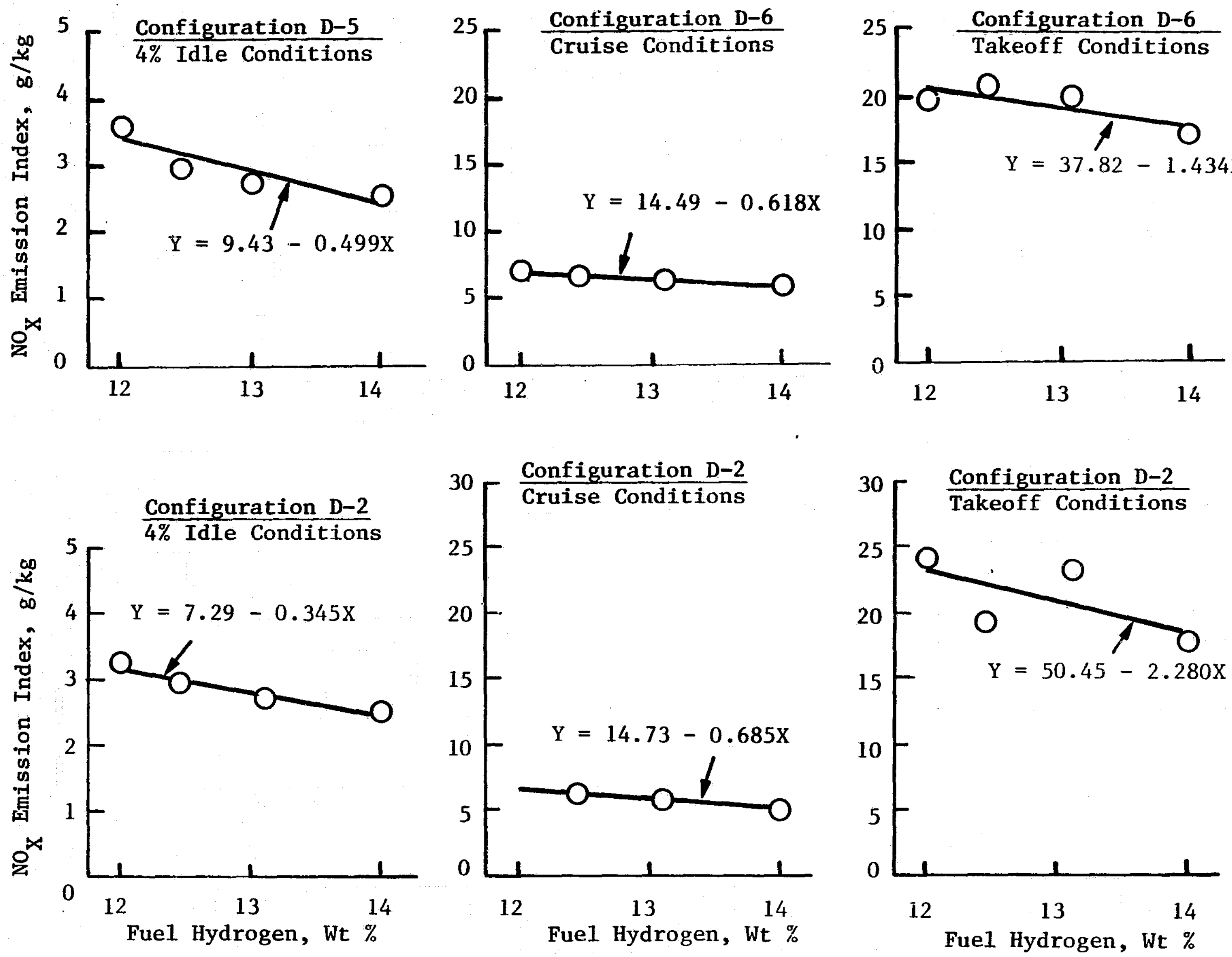

Figure 6-48. Effect of Fuel Hydrogen Content on Double-Annular Combustor Oxides of Nitrogen Emission.

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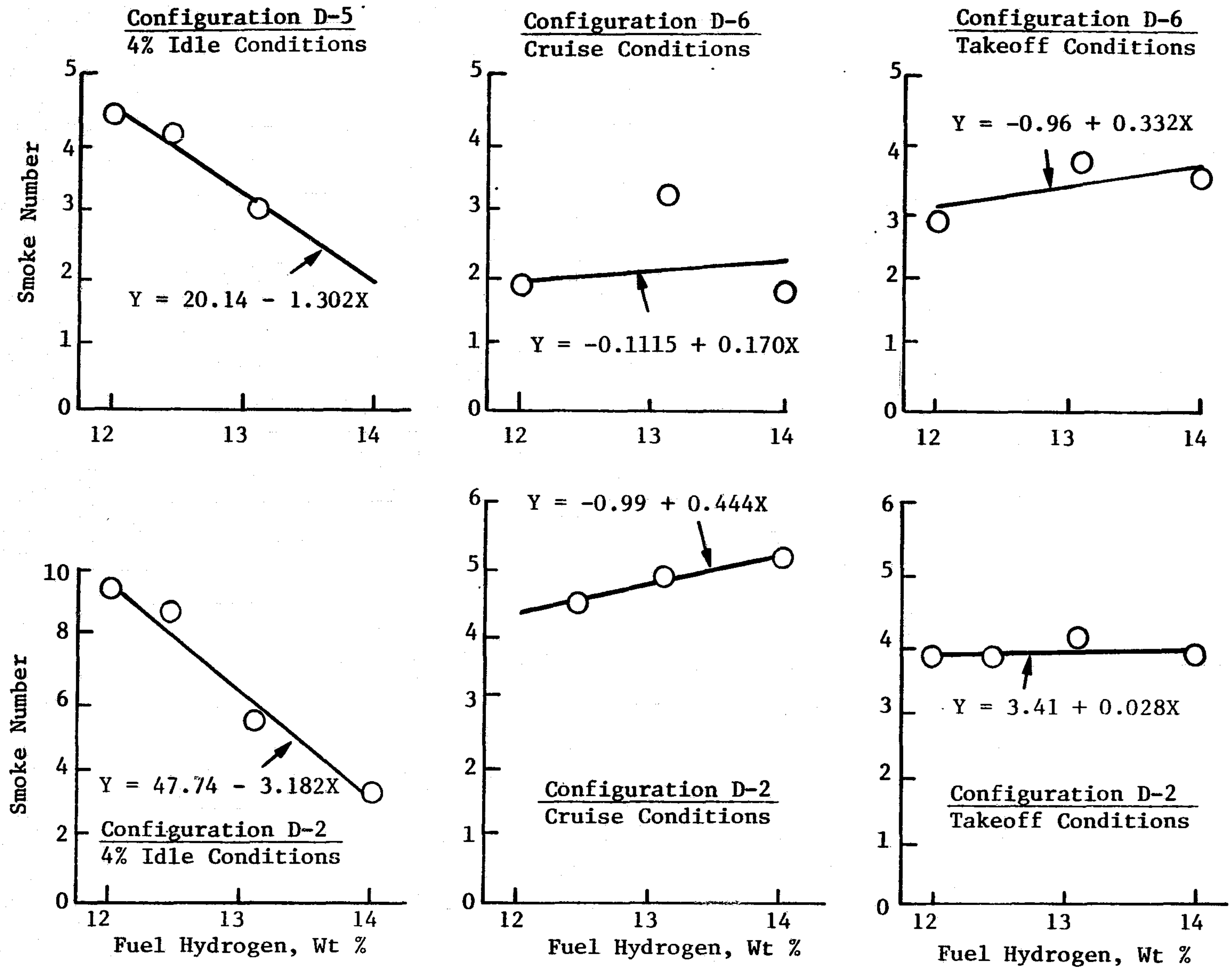

Figure 6-49. Effect of Hydrogen Content on Double-Annular Combustor Smoke Emissions.

Table 6-4. Effect of Fuel Hydrogen Content on Double-Annular Combustor EPA Parameters

Fuel	Emission	Emmision Index, g/kg				EPA Parameter, g/kN	
		Idle (a)	Approach	Climb	Takeoff	Calculated	Goal
ERBS 12.8	-CO	29.4	6.2	0.8	0.5	35.9	25.0
	-HC	3.1	0.7 a	0.8	0.7	4.7	3.3
	-NO_X	2.8	11.7	15.3 (b)	19.9	35.1	33.0
	-Smoke Number	3.0	6.6	-	3.7	3.7	19.2
Jet-A	-CO	26.4	4.2	0.3	0.2	30.8	25.0
	-HC	2.4	0.4	0.4	0.3	3.3	3.3
	-NO_X	2.6	11.3	13.2	17.1	31.3	33.0
	-Smoke Number	-	1.5	1.7	3.5	3.5	19.2

(a) Configuration D-5. All others are configuration D-6.

(b) Corrected to design fuel flow split (Wf P/W ft = 0.33)

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6.2.3.2 Performance

Double-annular combustor average liner temperatures at the idle, cruise, and takeoff conditions are shown as a function of fuel hydrogen content in Figure 6-50. Similar plots of maximum liner temperatures are presented in Figure 6-51. All of the liner temperatures in both of the configurations were insensitive to changes in fuel hydrogen content, and there was no consistent trend toward increased liner temperatures with reduced fuel hydrogen content, as in the sinlge-annular combustor. The low liner temperature sensitivity to fuel hydrogen content at the cruise and takeoff conditions is consistent with smoke emission results which indicated low smoke sensitivity at these conditions. However, smoke at idle was very sensitive to fuel hydrogen content, while liner temperatures are not.

Double-annnular combustor pilot dome flame radiation levels tended to increase slightly at the curise and takeoff operating conditions, as shown in Figure 6-52, but this increase had a minimal effect on liner temperatures. As shown in Figure 6-53, neither the inner nor outer liner temperatures were influenced by fuel properties.

Profile and pattern factor results with double-annular combustor Configuration D-6 are shown in Figure 6-54. At cruise conditions and, to a lesser degree, at takeoff there is a slight tendency toward increased pattern factors with increasing hydrogen content. However, this effect is small.

Combustor blowout fuel/air ratio at idle conditions tended to increase with decreasing hydrogen content, as shown in Figure 6-55; but again, this effect was small. No altitude relight/blowout data were obtained with the double-annular combustor.

Other aspects of combustor performance, including combustion efficiency and combustor pressure drop, were not significantly affected by fuel properties, although combustion efficiency did tend to increase very slightly as fuel hydrogen was increased (and CO was reduced).

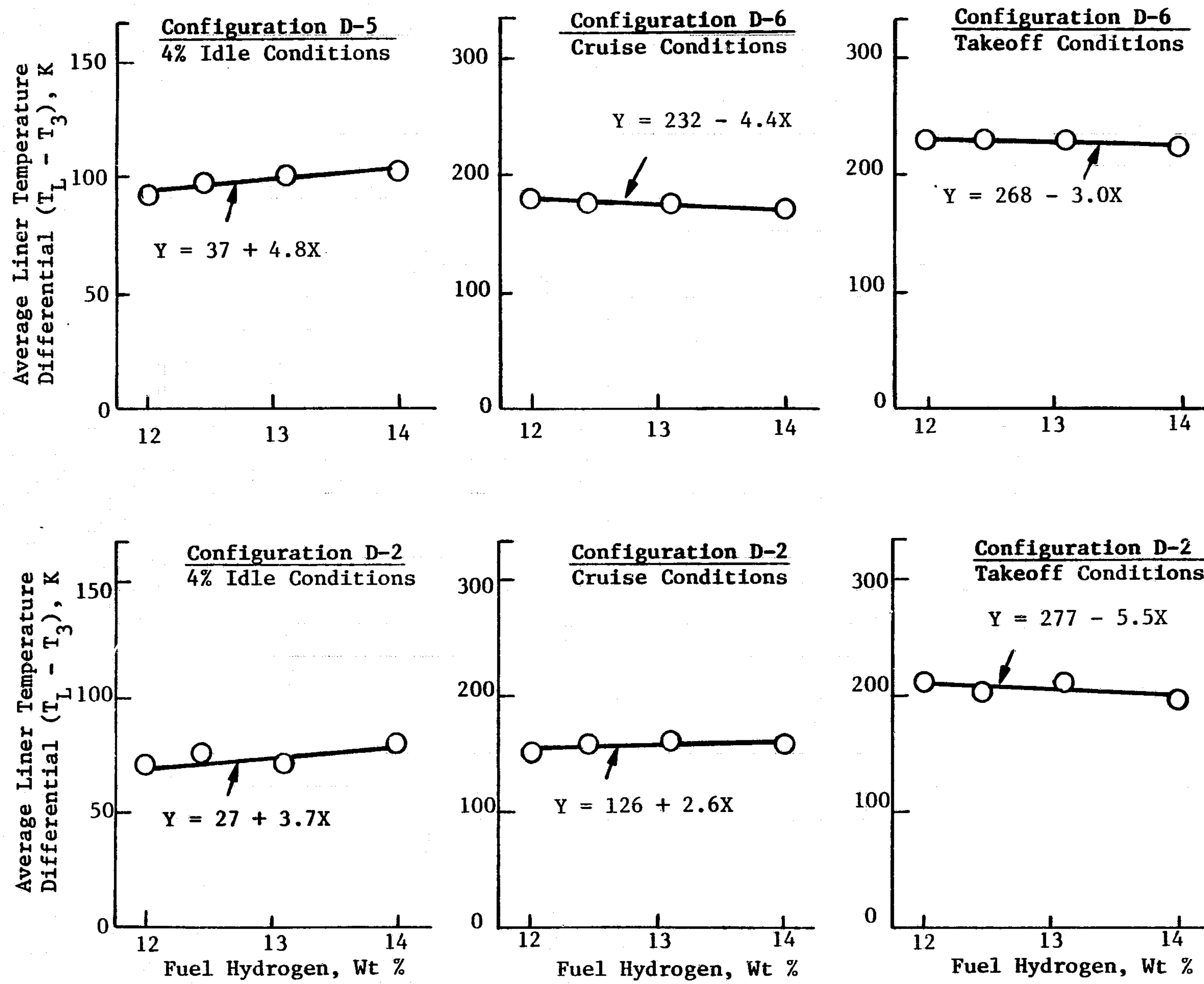

Figure 6-50. Effect of Fuel Hydrogen Content on Double-Annular Combustor Average Liner Temperatures.

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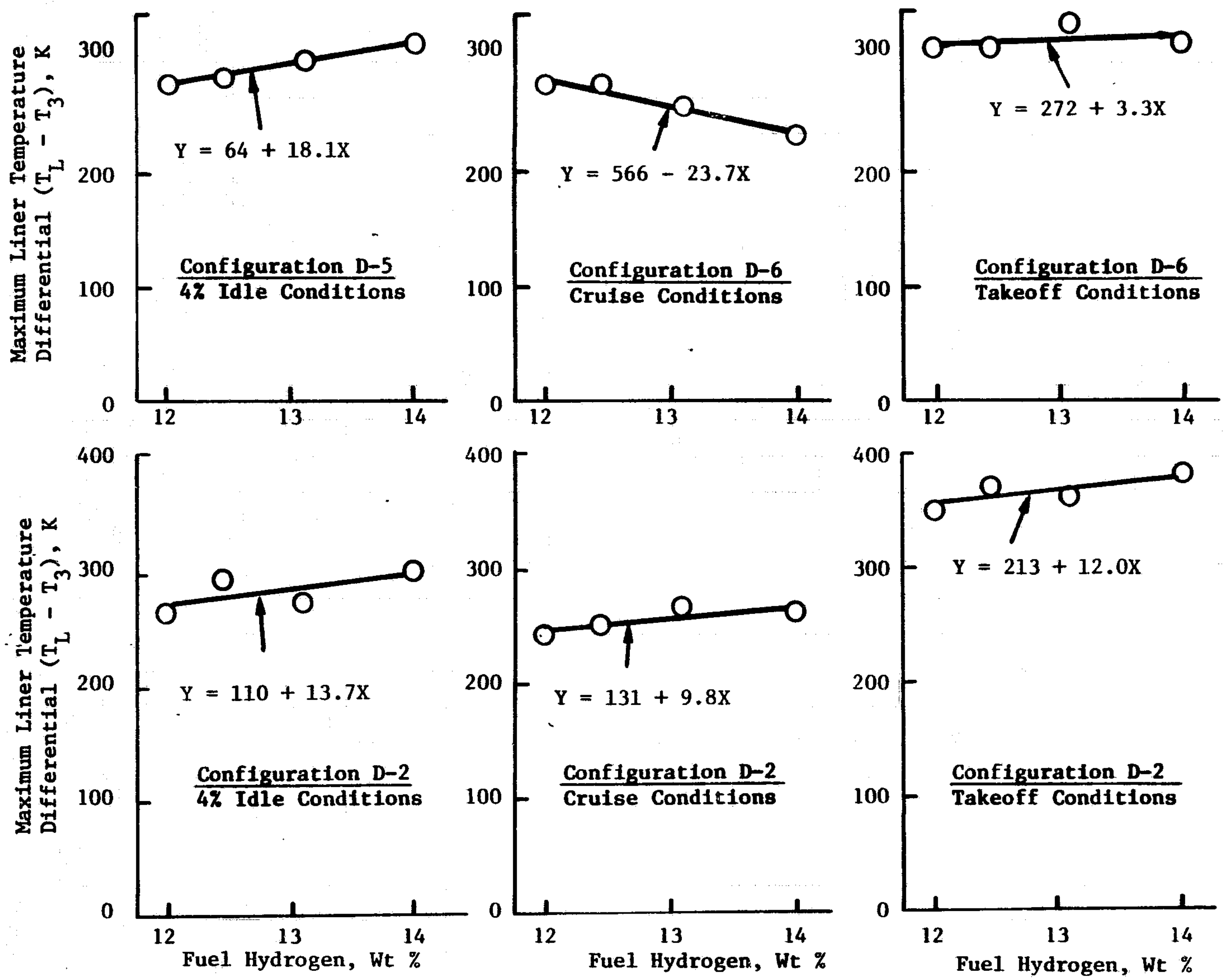

Figure 6-51. Effect of Fuel Hydrogen Content on Double-Annular Combustor Maximum Liner Temperatures.

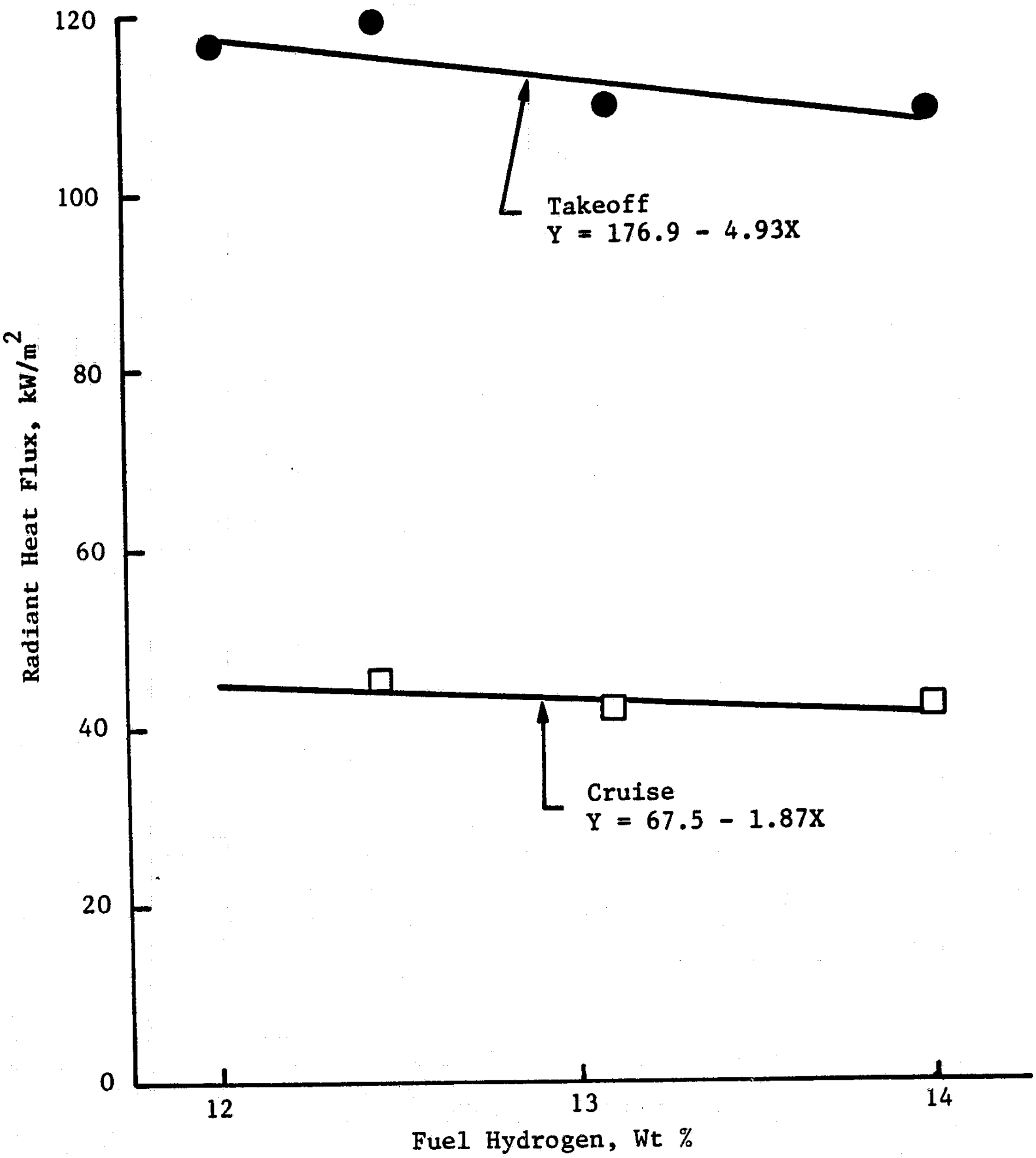

Figure 6-52. Effect of Fuel Hydrogen Content on Double-Annular Combustor Pilot Dome Radiation.

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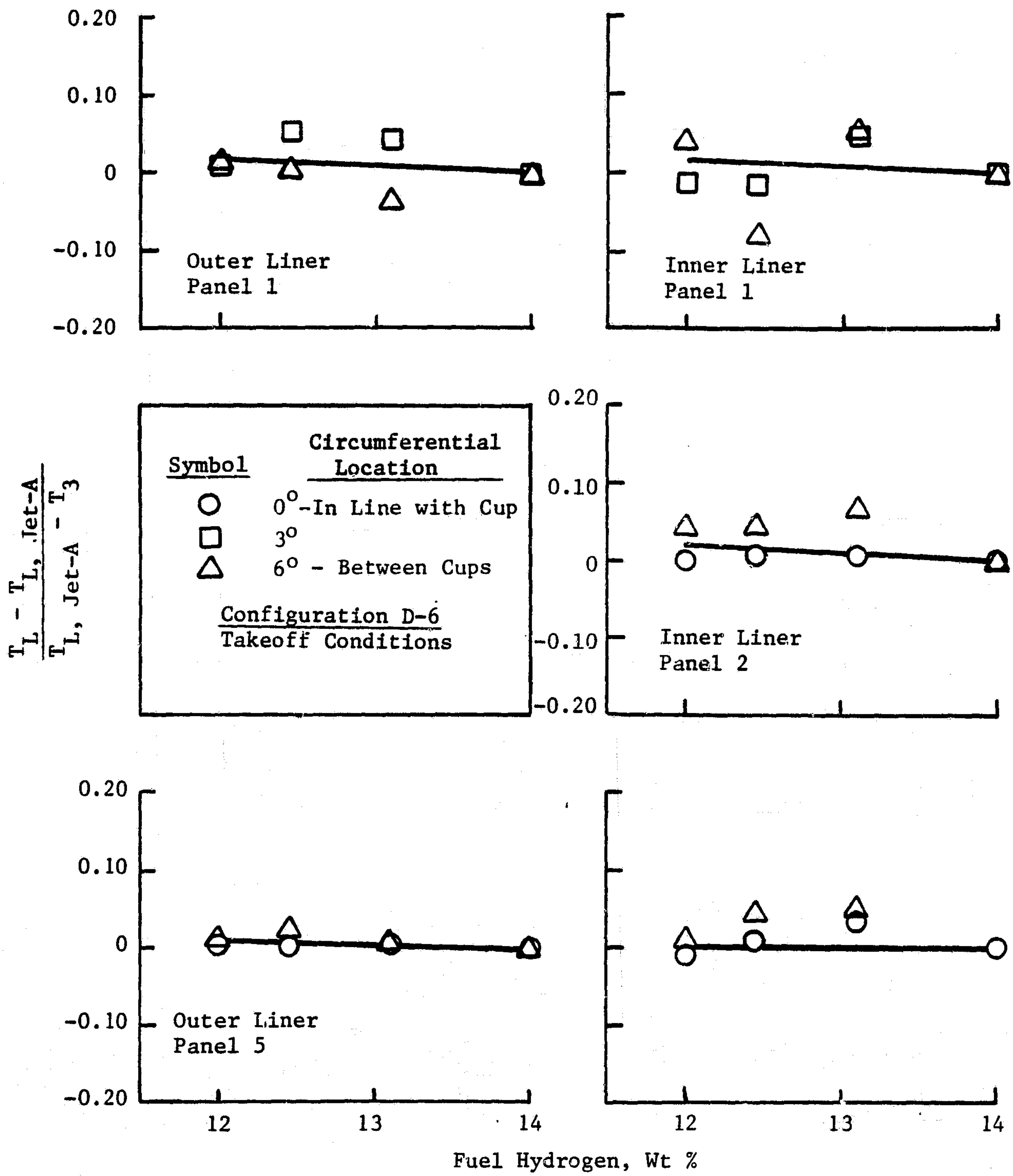

Figure 6-53. Effects of Fuel Hydrogen Content on Local Liner Temperature Parameter - Double-Annular Combustor Configuration D-6.

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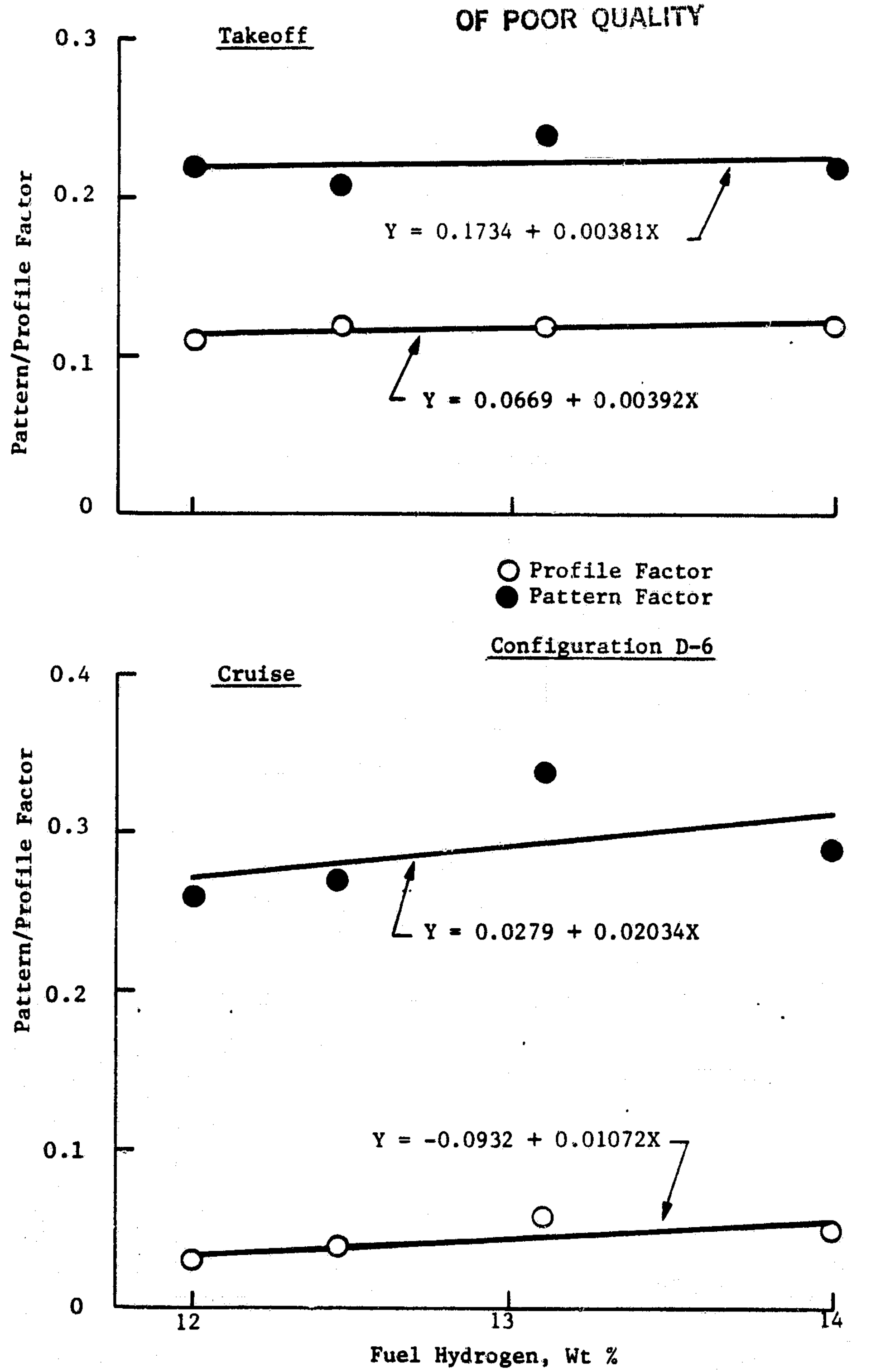

Figure 6-54. Effect of Fuel Hydrogen Content on High Power Exit Temperature Profile/Pattern Factor (Double-Annular Combustor).

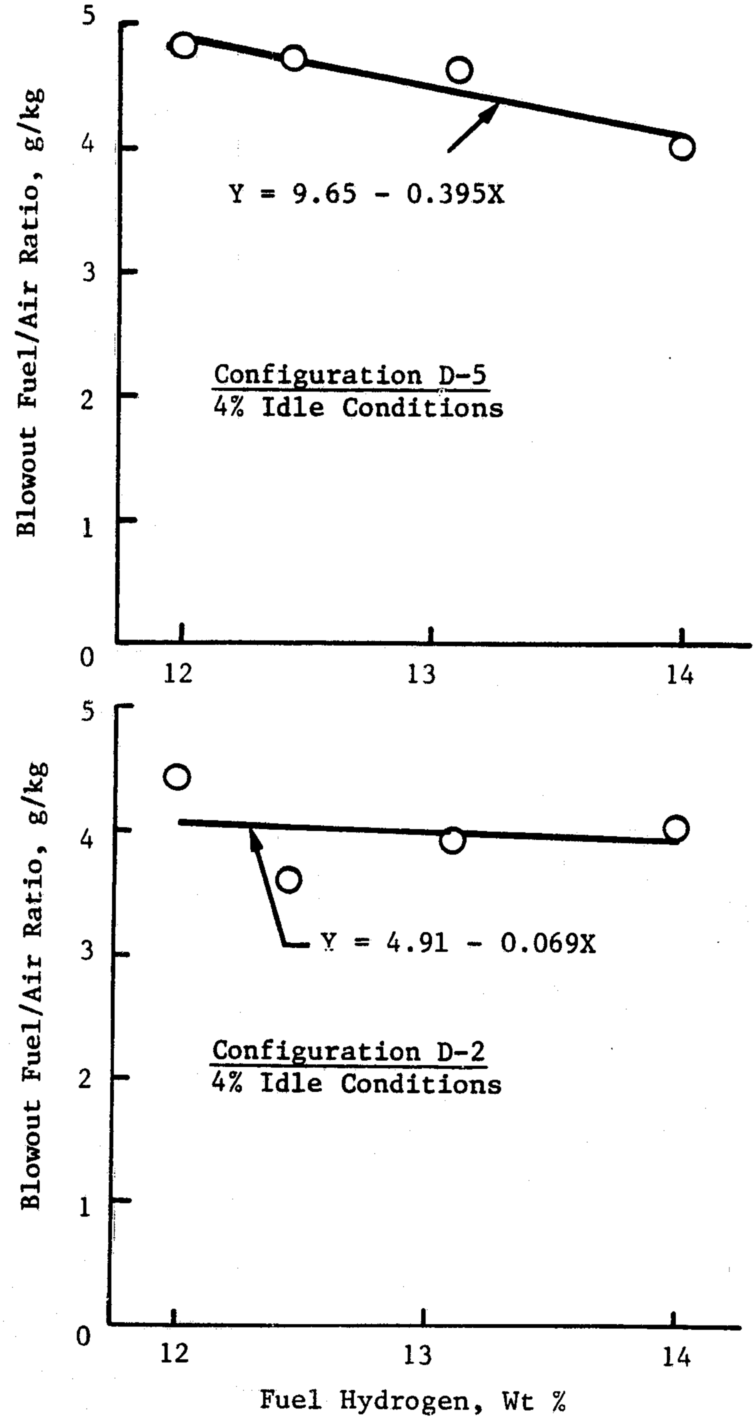

Figure 6-55. Effect of Fuel Hydrogen Content on Double-Annular Combustor Idle Blowout.

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Overall, performance of the double-annular combustor was found to be very insensitive to variation in fuel properties. No significant performance deterioration was noted over the range of fuel properties evaluated.

6.3 SHORT SINGLE-ANNULAR VARIABLE-GEOMETRY COMBUSTOR

6.3.1 General Emissions and Performance Characteristics

The emissions and performance characteristics of the variable-geometry combustor at any given operating condition will depend to a large extent on the variable-geometry swirler setting. Therefore, the variable swirler actuation must be scheduled to provide appropriate airflow levels at all operating conditions. Furthermore, it is desirable to open the swirler at as low a power level as possible in order to reduce combustion system pressure drop at higher power levels.

As discussed previously, the variable-area swirler used in this program was designed to be capable of operation in a continuously variable mode, where the vanes are opened gradually to optimize primary zone stoichiometry as engine power level is increased. Figure 6-56 shows a tentative actuation schedule for continuous variation and an alternative schedule for discrete variation, where the vanes are rapidly actuated from the fully closed position to the fully open position at a specified power level or fuel/air ratio. In Figure 6-56, the variable vane position is shown both as a function of sea level thrust and combustor fuel/air ratio. Combustor fuel/air ratio is the preferred control variable for variable vane position since the combination of fuel/air ratio and vane position determines combustor stoichiometry, which is the key variable in determining combustor emissions and performance. The same vane position versus fuel/air ratio curve would be recommended for steadystate and transient operation. In both of the indicated actuation schedules, the vanes are in the fully closed position at idle conditions and below, and are in the fully open position at the climb and takeoff condition. The variable vanes are also fully open in the normal cruise position to minimize combustor pressure drop. In the discrete variable geometry mode, the vanes

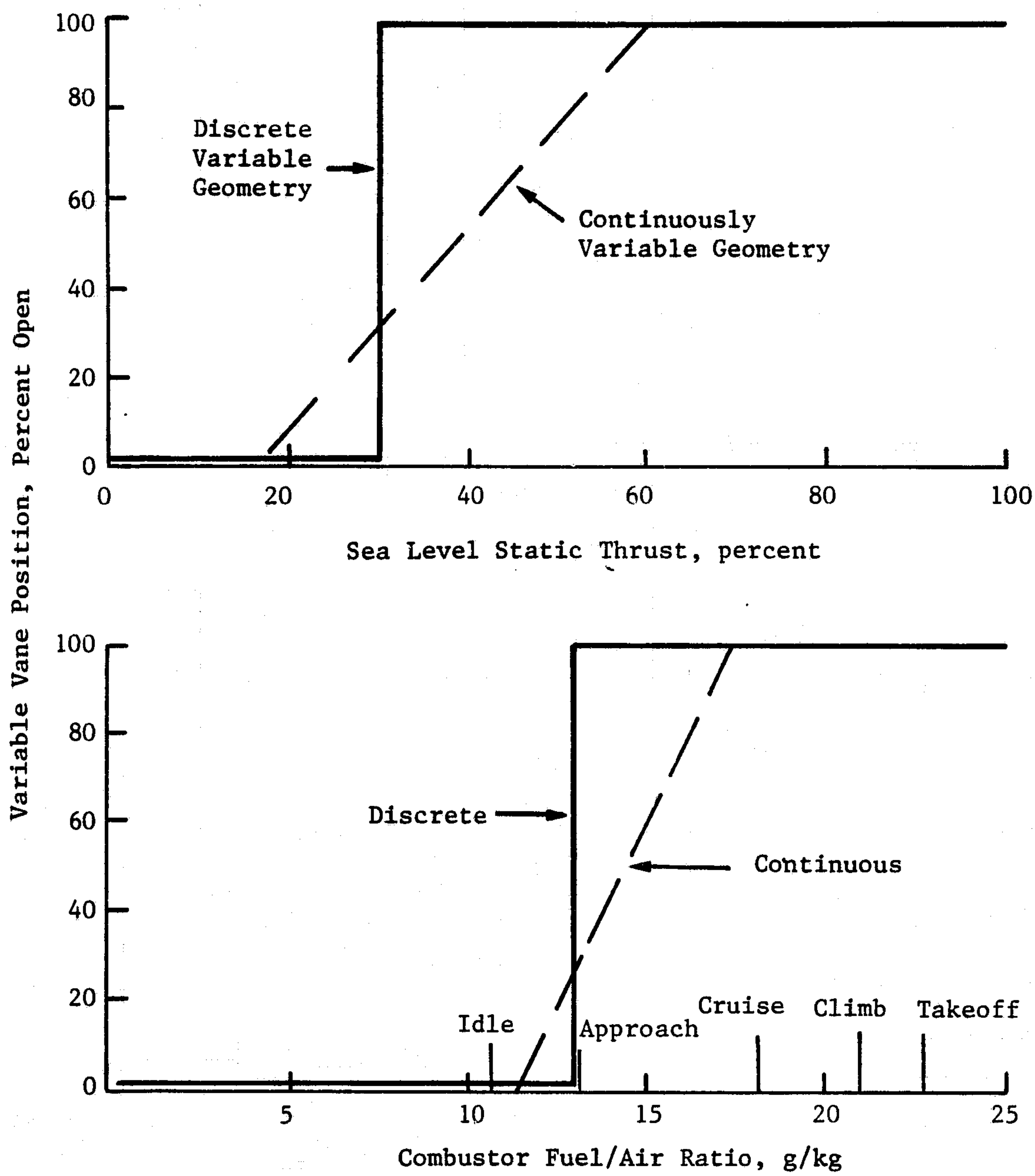

Figure 6-56. Variable-Geometry Actuation Schedule Alternatives.

would be opened near the 30% thrust level; while in the continuous mode, the vanes would be opened gradually between about 20% and 60% of rated thrust. With the selected actuation schedules, the vanes would be fully open during most engine acceleration, thereby improving compressor stall margin. Conversely, the vanes would be closed during deceleration, where stall margin is not a factor, to provide improved combustor blowout margin.

In the tests of the variable geometry combustor, virtually all of the idle data were obtained with the vanes closed, and all high power data were taken with the vanes open. In several cases, the variable-vane setting was actuated at the approach condition to determine the effects of variation in swirler airflow. A few parametric test points were also run to simulate failure of the actuation system in the fully closed positions.

In the following discussions, the general emissions and performance characteristics of the variable-geometry concept are illustrated primarily by results obtained with two of the final combustor configurations evaluated in the test program (Configurations V-7 and V-8). As with the final double-annular configuration, these two combustors varied only in the flow rating of the fuel nozzle tip. Configuration V-7 used a simplex, pressure atomizing tip, sized for operation at idle conditions, while Configuration V-8 incorporated the same type of tip, sized for operation at takeoff conditions. Taken together, these tips are representative of dual orifice fuel injector.

These two variable-geometry configurations were run at actual engine pressure at all operating conditions, except for two test points at the approach conditions, run with Configuration V-7. Pressure was reduced at these points because of fuel nozzle flow limitations.

6.3.1.1 Emissions

Variable-geometry cumbustor CO and HC emissions characteristics over the combustor operating range are illustrated in Figure 6-57. CO and HC both decrease rapidly as thrust is increased from idle to approach conditions with the variable swirler vanes closed. When the vanes are opened at the approach condition, CO and HC are increased to levels slightly

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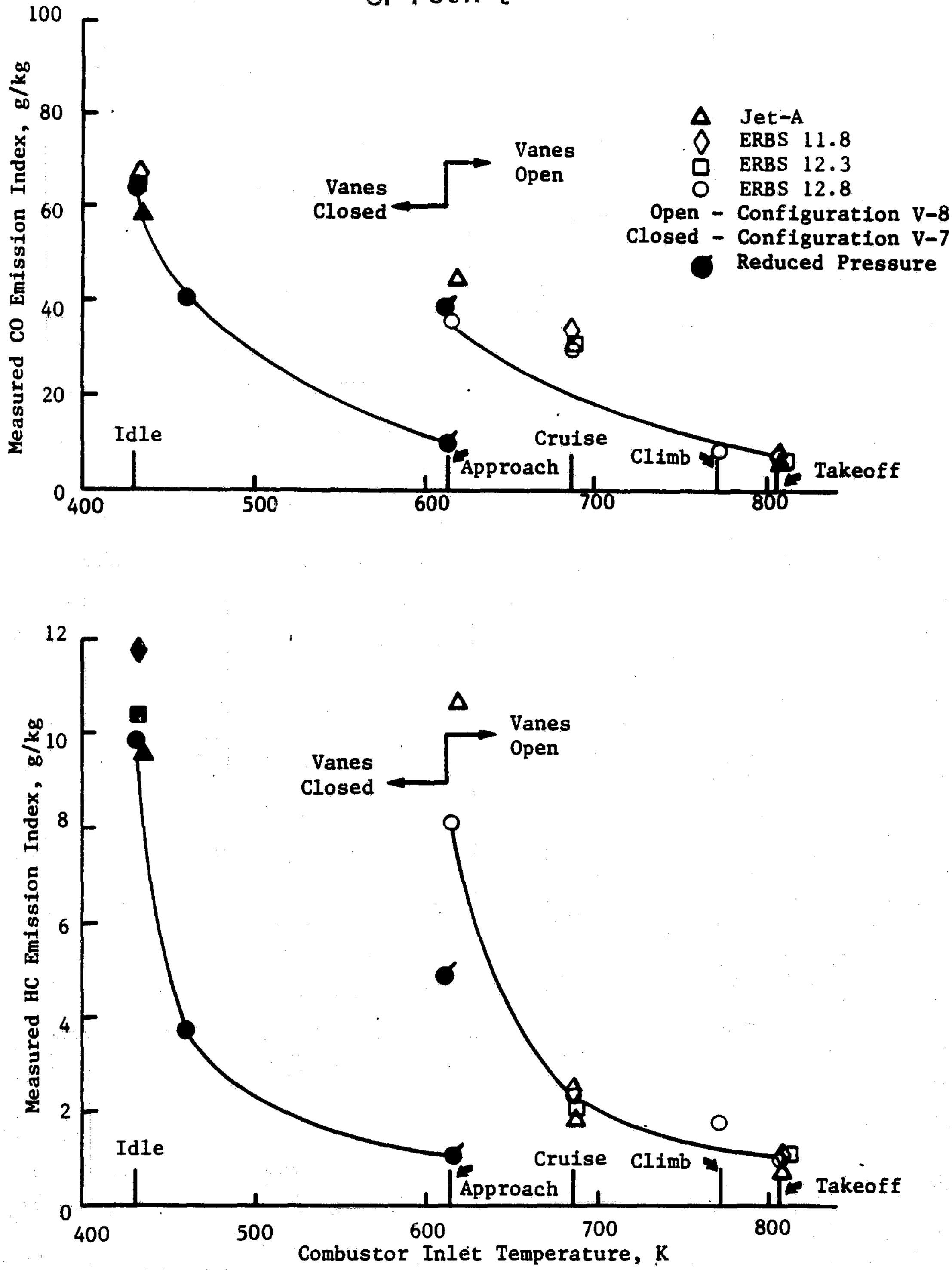

Figure 6-57. Variable-Geometry Combustor CO and HC Emissions.

lower than at idle. Above approach, the CO and HC levels again decrease rapidly.

At idle condtions, the minimum CO levels are obtained very near the idle design point fuel/air ratio as shown in Figure 6-58. This confirms that the primary zone stoichiometry is appropriate with the vanes closed for the reference engine cycle idle condition.

The effect of variable area vane setting on CO and HC emissions at approach was investigated in two of the variable geometry combustor configurations by running with the vane 50% open, as well as fully open and fully closed at the approach operating conditions. As shown in Figure 6-59, CO and HC emissions were nearly constant between the fully closed and 50% open positions. Both CO and HC then increased rapidly as the vanes were opened further.

Emissions characteristics of NO_x and smoke over the variable-geometry combustor range of operation are shown in Figure 6-60. Both of these emissions increased as thrust was increased, except for a slight reduction when the variable vanes were opened at the approach condition. As shown in Figure 6-61, NO_x emissions at the approach operating conditions decreased linearly as the vanes were opened and the primary zone equivalence ratio was reduced. Smoke also tended to decrease as the vanes were opened initially and the primary dome became leaner. However, smoke level tended to increase very slightly between 50% and 100% vane opening. It is thought that this effect is a result of change in the fuel spray distribution as the vanes were opened. Results of atmospheric pressure swirl cup spray patternation tests indicated that the fuel spray angle increased when the vanes were opened. This would normally tend to reduce smoke emission, unless locally rich streaks were present.

EPA parameter values for the variable geometry combustor, for three different approach power variable vane settings, are presented in Table 6-5. Emissions levels are similar with the vanes in the closed and 50% open position at approach. With the vanes fully open, the CO and HC parameters are increased by 20% to 30%. CO and HC are both well above the program goals. Reductions of 70% from current CO and HC levels are needed

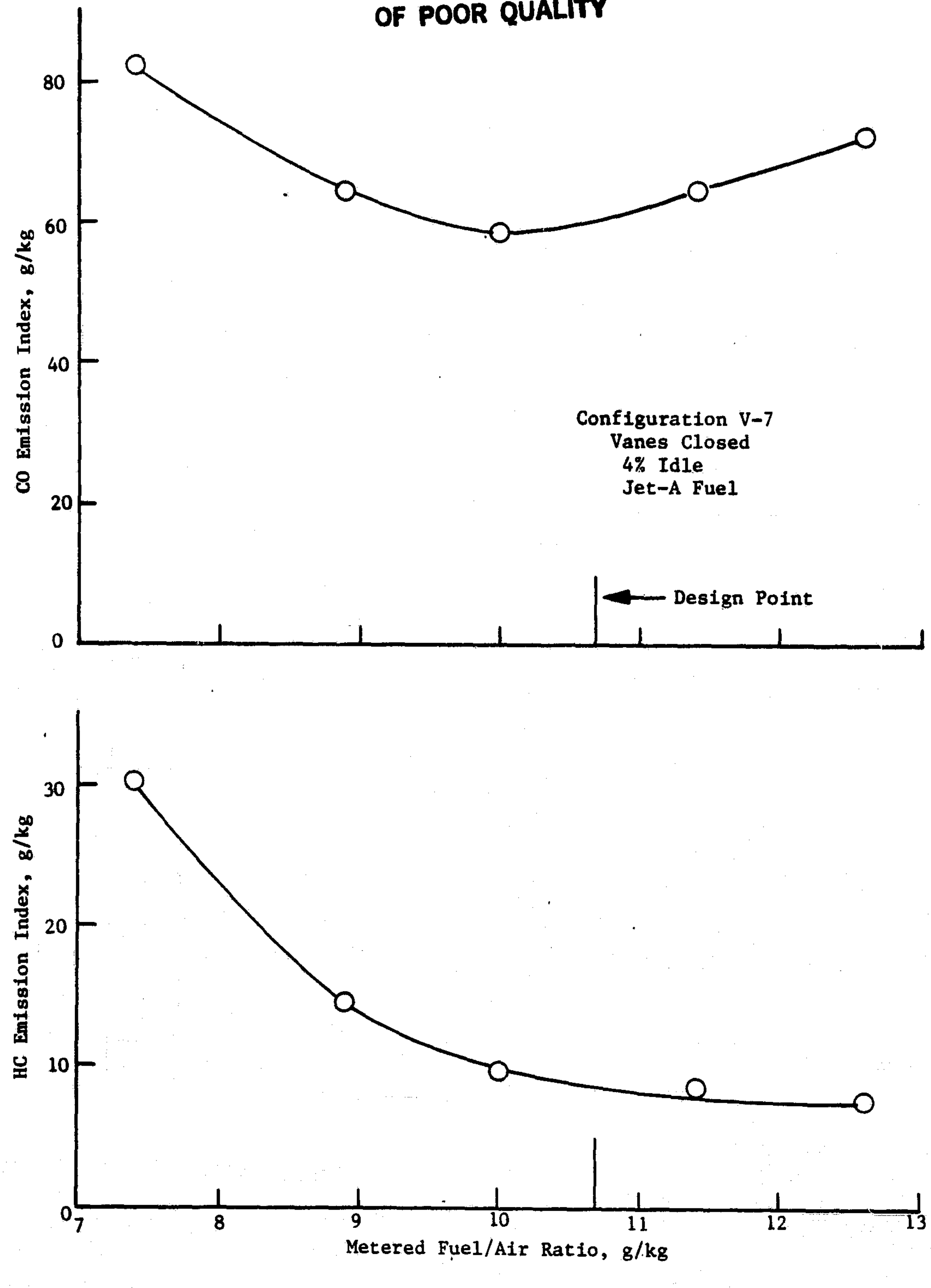

Figure 6-58. Effect of Fuel/Air Ratio on Variable-Geometry Combustor CO and HC Emissions at Idle.

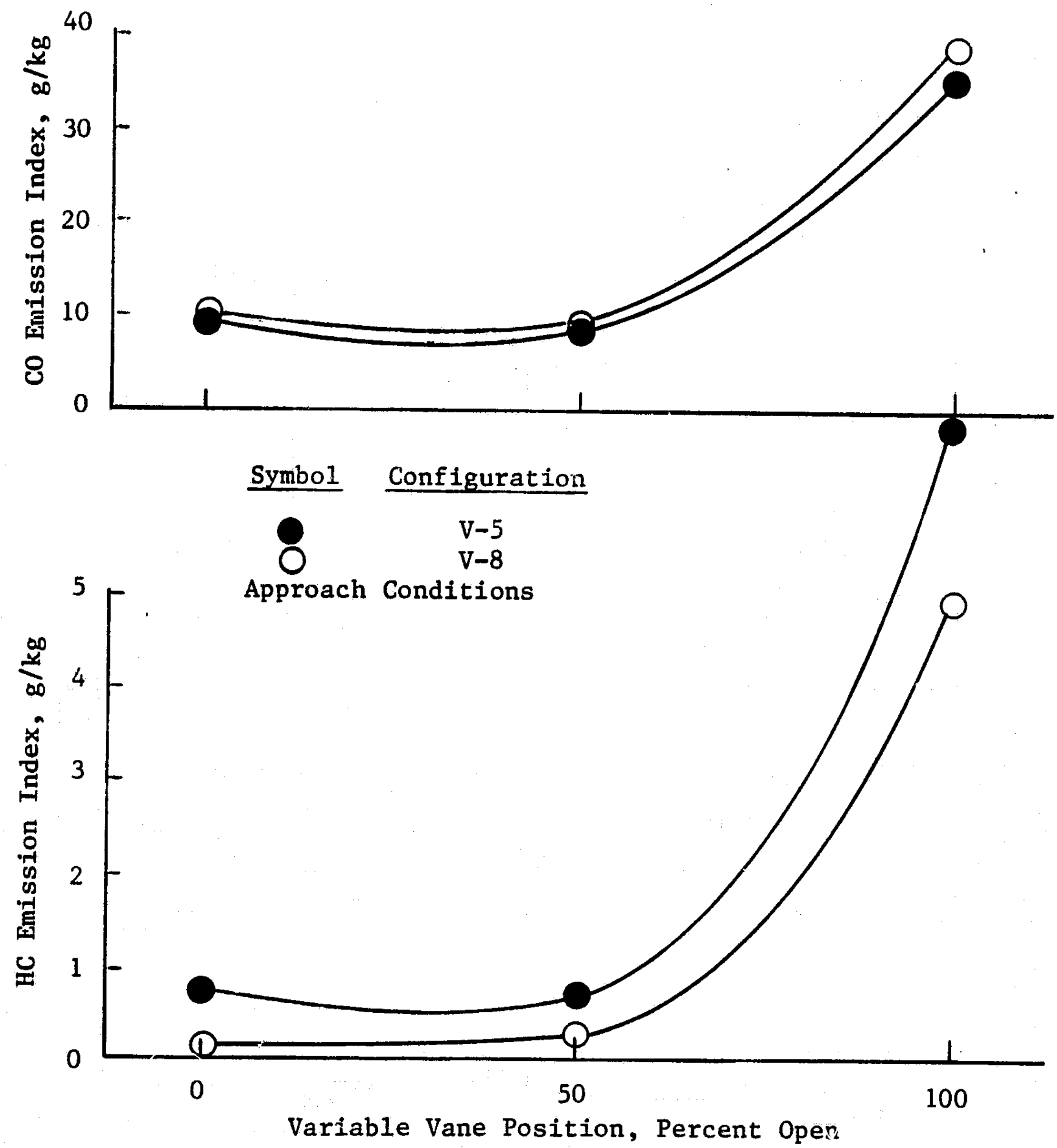

Figure 6-59. Effect of Variable Vane Position on Variable-Geometry Combustor CO and HC Emissions at Approach.

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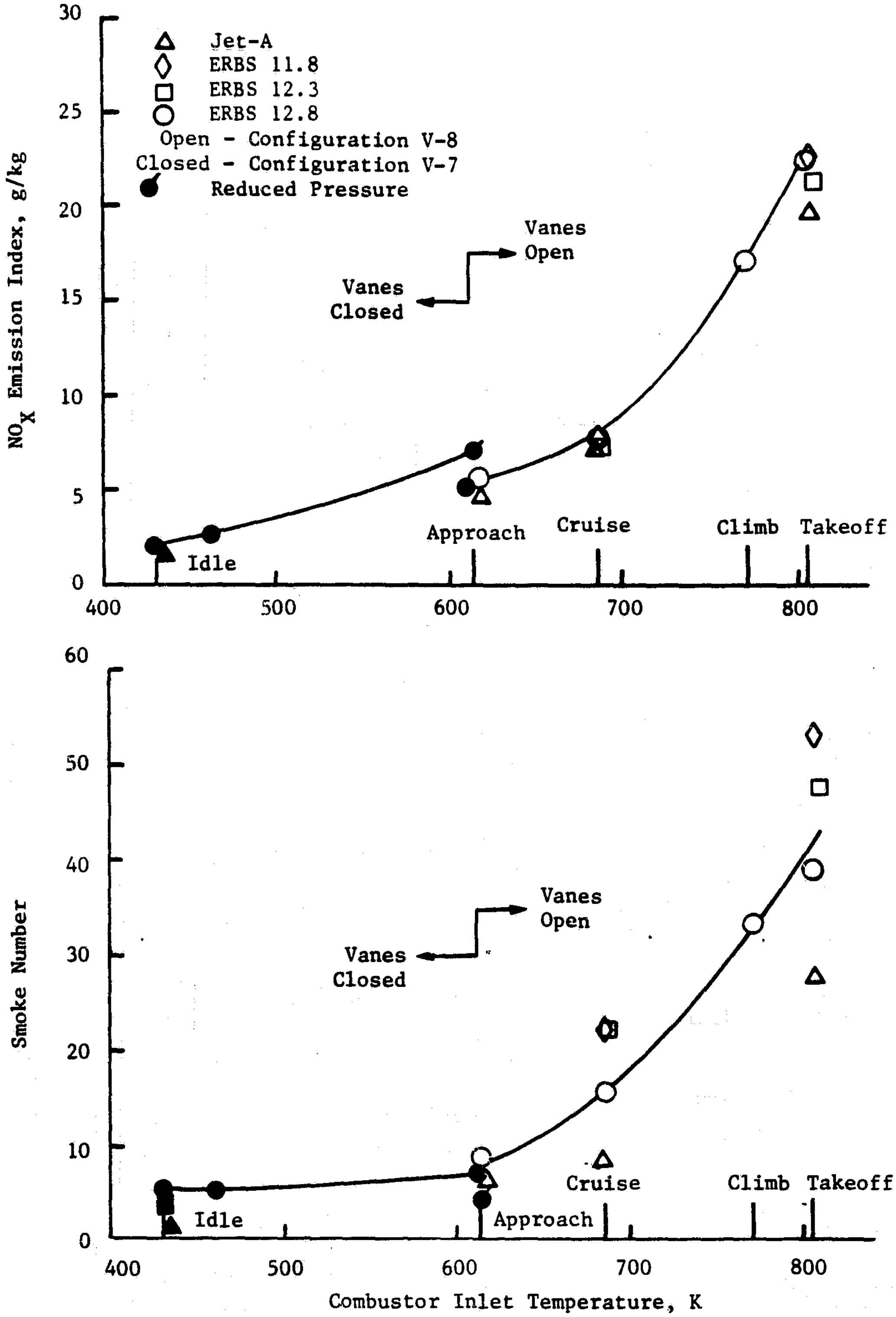

Figure 6-60. Variable-Geometry Combustor NO_X and Smoke Emissions.

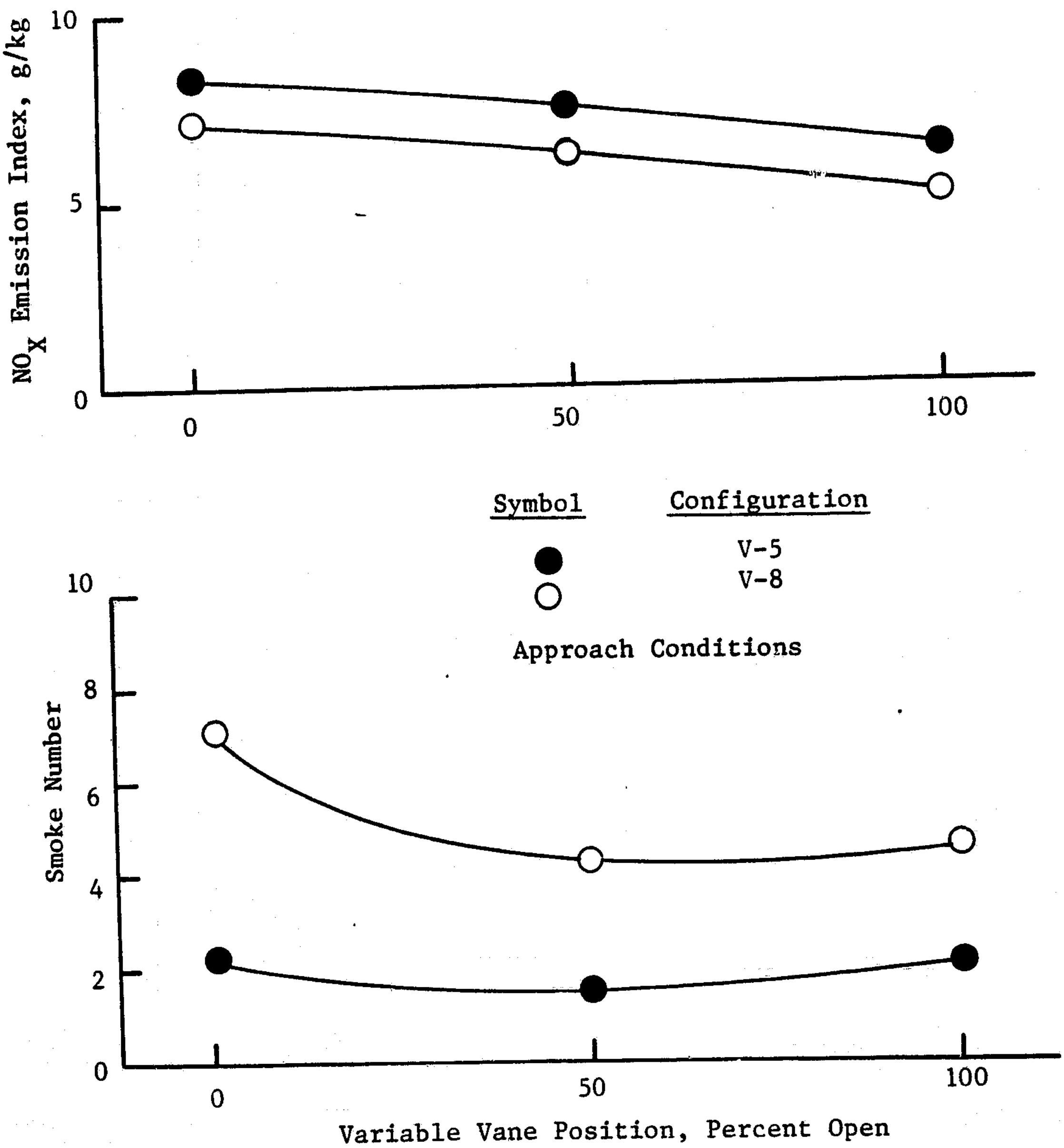

Figure 6-61. Effect of Variable Vane Position on Variable-Geometry Combustor NO_X and Smoke Emissions at Approach.

Table 6-5. Variable-Geometry Combustor EPA Parameters (EBRS 12.8 Fuel).

Approach Power Vane Position, Percent Open	EPA Parameters, g/kN			Maximum Smoke Number
	CO	HC	NO_x	
0 (closed)	82.5	10.1	34.7	39
50	81.6	10.2	34.0	39
100 (open)	99.9	13.0	33.3	39
Goal	25.0	3.3	33.0	19.2

to meet the goals. However, the idle emissions levels are about the same as those obtained with the double-annular combustor at a similar stage of development (at the end of Phase I of the NASA/GE Experimental Clean Combustor Program). CO and HC EPA parameter levels for the variable-geometry concept, when operated in the high power mode (with the vanes open) at approach are also lower than levels obtained with the double-annular concept when uniform two-stage burning is used at approach, even though idle emissions are somewhat higher with the variablegeometry burner. The variable-geometry combustor NO_x EPA parameter closely approaches the program goal and is relatively insensitive to the approach operating mode. A smoke emission reduction of about 50% is also needed, based on results obtained with Configuration V-8, but lower smoke levels were demonstrated in other configurations of this concept.

6.3.1.2 Performance

Average and maximum liner temperature differentials for the final variable-geometry combustor configurations are shown in Figure 6-62. Average and maximum temperatures both increased with increasing power level. Both maximum and average liner temperatures were low, with maximum measured temperature differentials at takeoff conditions being about 80 K below the program goal. The location of maximum temperatures for this concept was on the aft panel of the outer liner.

Primary zone radiant heat flux characteristics of the final variable-geometry combustor configuration are shown in Figure 6-63. Radiation data were not obtained with the vanes closed with this final configuration due to an instrument malfunction. Radiant heat flux generally increased with power level during operation above the approach power level.

The effects of variable-swirler vane position on combustor liner temperatures and radiant heat flux at approach conditions are shown for two different variable-geometry combustor configurations in Figure 6-64. As the vanes are opened and swirler airlfow is increased, primary zone flame luminosity and bulk temperature are both reduced, which tends to reduce convective and radiative heat transfer to the combustor liners. On the other hand, the velocities within the combustor are increased and film

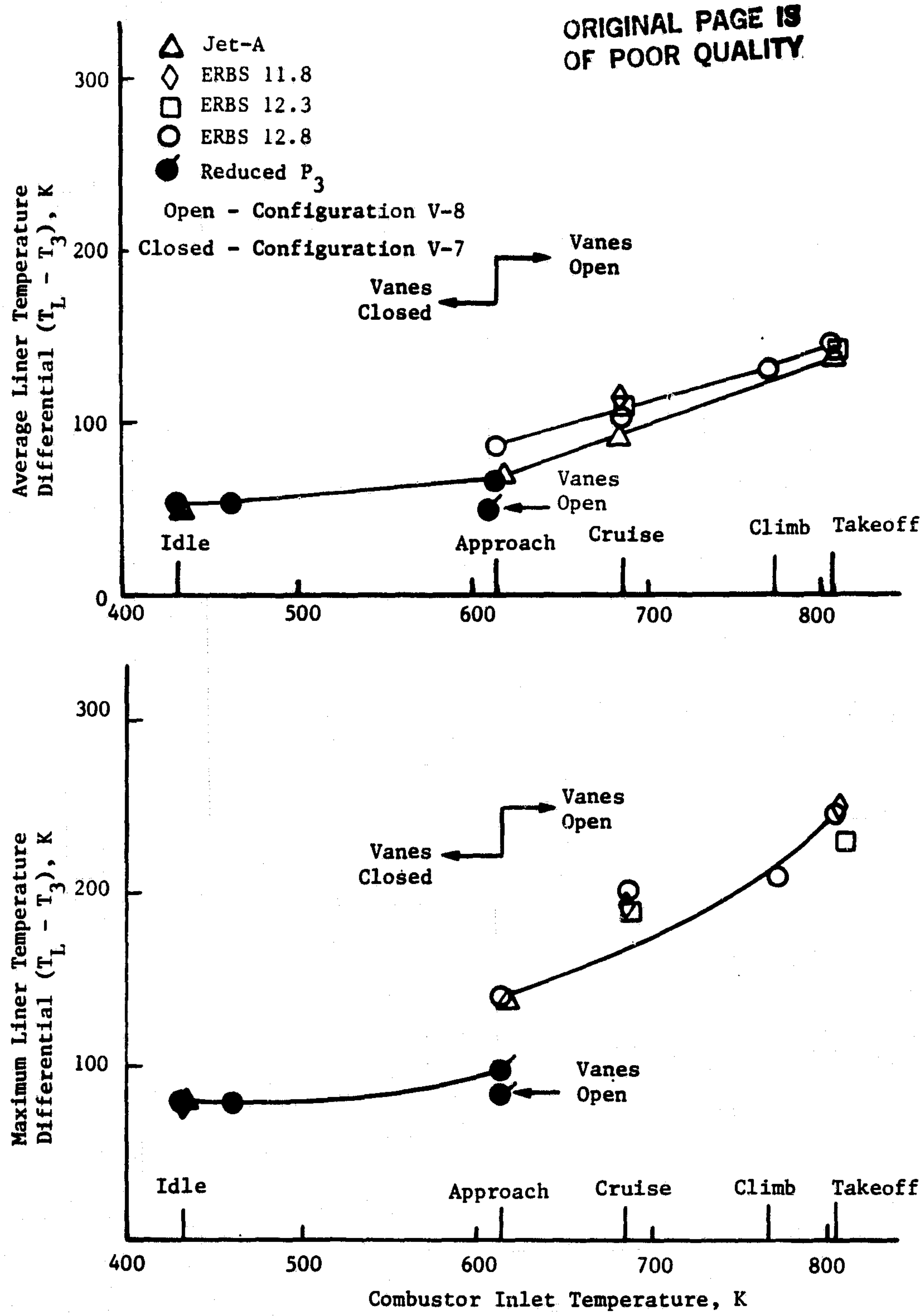

Figure 6-62. Variable-Geometry Combustor Average and Maximum Liner Temperatures.

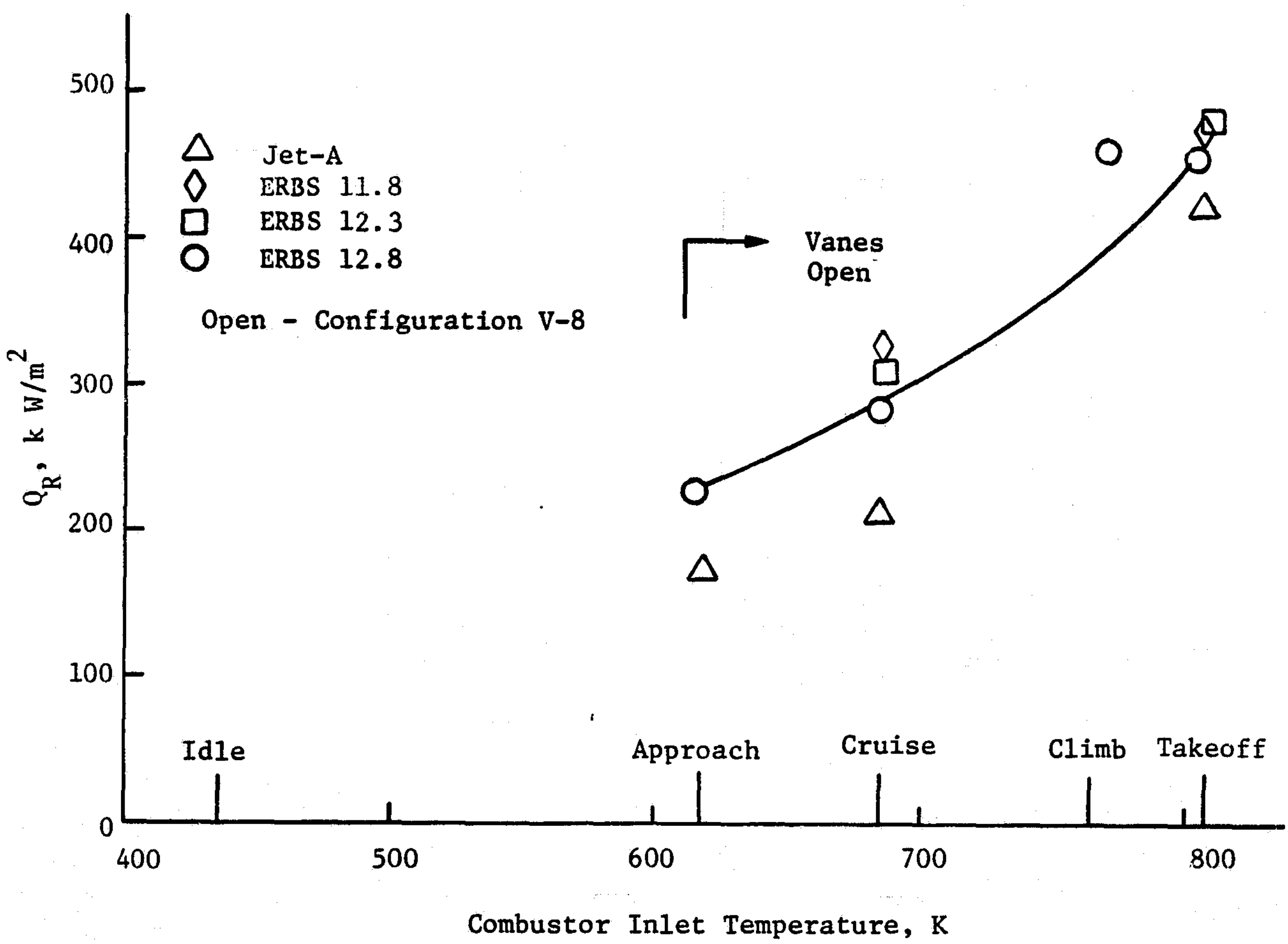

Figure 6-63. Variable-Geometry Combustor Radiant Heat Flux.

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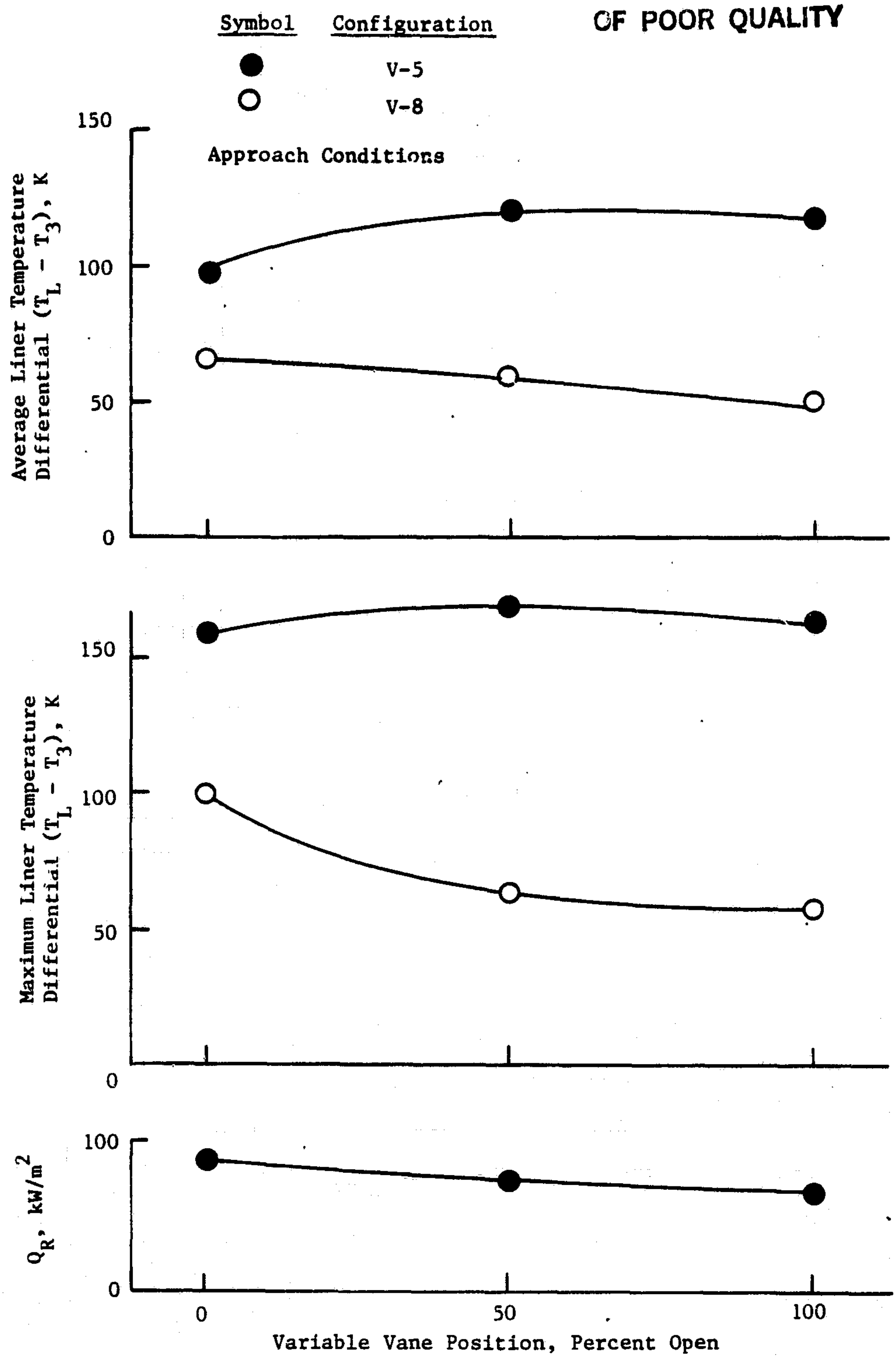


Figure 6-64. Variable-Geometry Combustor - Effect of Vane Position on Approach Liner Temperatures and Flame Radiation.

cooling flows are reduced, which tends to increase liner convective heat loading. In Configuration V-5, which had reduced film cooling flows on the combustor liners for emissions reduction, the further reduction in cooling flow as the vanes were open caused liner temperatures to increase slightly, even though radiant heat flux was reduced. In Configuration V-8, which had higher cooling flow levels and thermal barrier coatings, liner temperatures decreased as the vanes were opened.

Variable-geometry combustor exit temperature profiles for Configuration V-7 at the idle (vanes closed) operating condition and for Configuration V-8 at takeoff (vanes opened) conditions are shown in Figure 6-65. The profiles shown in this figure were calculated from individual gas samples and, at the takeoff condition, thermocouple data. Thermocouple data at idle were not used because conduction measurement errors are large at the low pressure conditions with the thermocouple rakes used in these tests. Exit profiles were similar at both conditions. Profiles were inboard peaked, and pattern and profile factors were well above the program goals. However, very little effort was expended to develop the exit temperature profile of this combustor concept during the Phase I program, so there is potential for improvement.

Postrun photographs of variable-geometry combustor Configurations V-4 and V-8 are shown in Figure 6-66. Both of these test combustors incorporated the same venturi extension, but Configuration V-4 used the baseline fuel injector tips, while Configuration V-8 used a simplex fuel nozzle tip design having a radial air shroud. Very light carboning of the venturi extension was evident with the baseline nozzles. However, heavier carboning resulted when the simplex fuel nozzles were used. The change in carboning characteristics is likely the result of a change in fuel droplet trajectories which affected the amount of fuel impinging on the venturi and venturi extension. If no fuel impinged on the venturi and extension, no carbon would be found. Even if a small proportion of the fuel impinged, the venturi and extension would run hot enough at high power conditions to burn off deposits as they were formed. On the other hand, if a large proportion of the fuel impinged, the venturi and extension would remain cool and deposits would not form. Carboning would only occur when

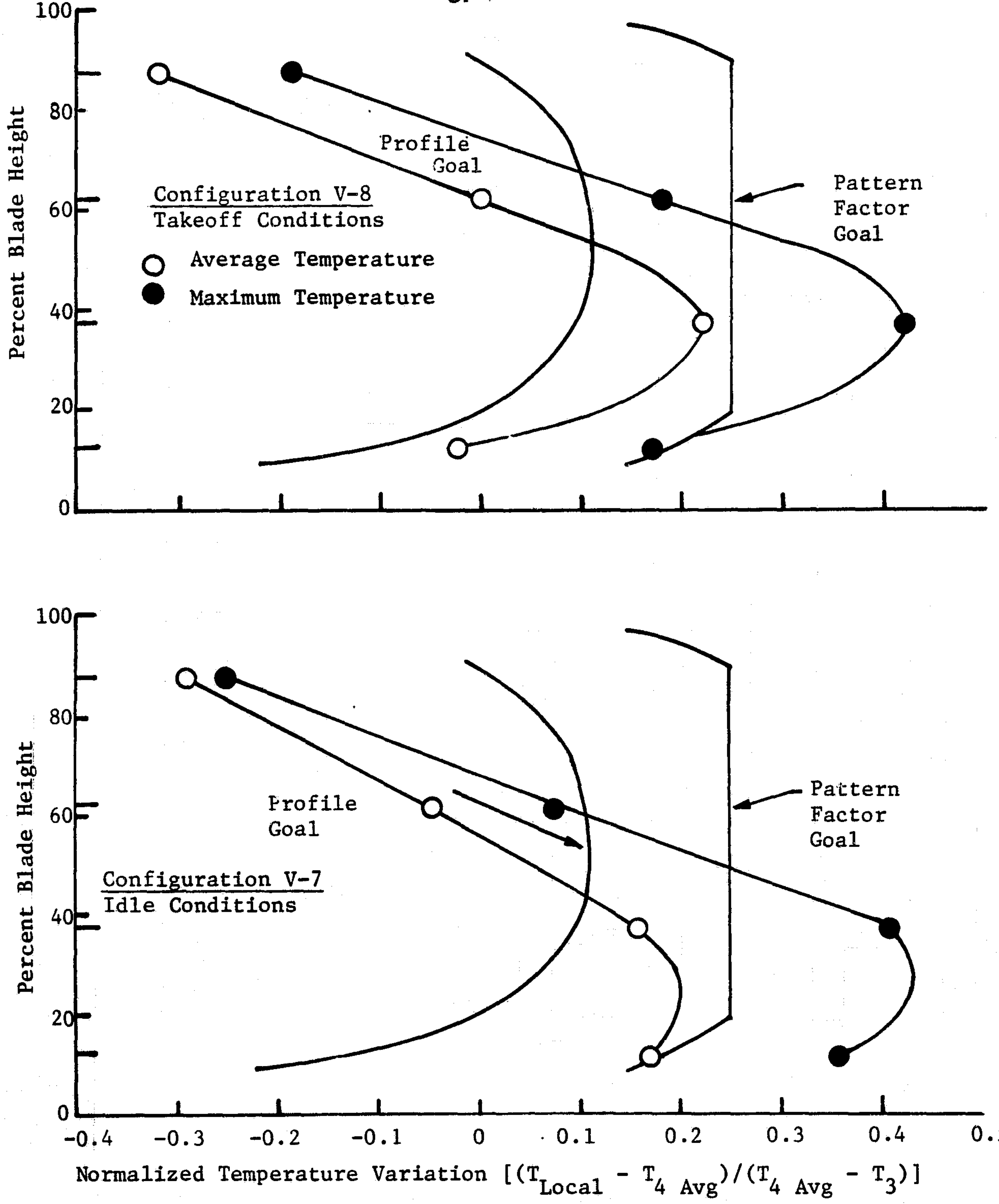


Figure 6-65. Variable-Geometry Combustor Exit Temperature Profiles.

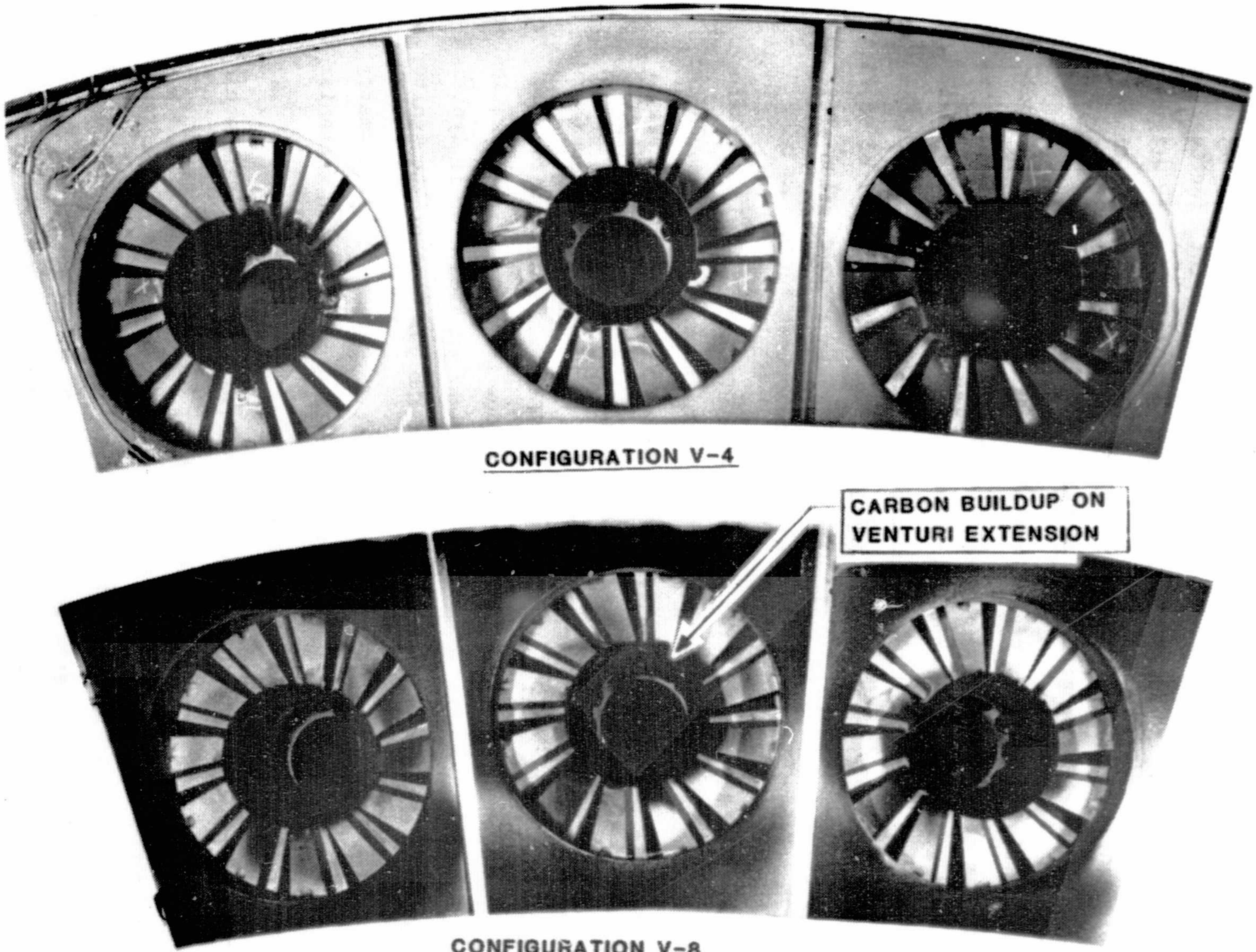


Figure 6-66. Post Run Photographs of Variable-Geometry Combustor Dome.

the amount of fuel on the venturi is sufficient to maintain metal temperatures in an intermediate range (probably 600 to 700 K) where the rate of carboning is faster than the rate of oxidation of the deposits.

Combustor pressure drop corrected to the design point, for Configurations V-7 and V-8 averaged 5.35% of combustor inlet pressure with the variable vanes closed and 4.06% with the vanes opened. Both of these values are below the program goal of 6%.

Combustion efficiency of the variable geometry combustor was above the program goal of 99% at the cruise, climb, and takeoff operating conditions, and at the approach operating condition with the variable area vanes in the fully closed or 50% open positions. At approach with the vanes fully open, combustion efficiency was reduced to a level of 98.7%, slightly below the program goal. At idle conditions, combustion efficiency ranged from 97.4% to 97.8% with the four test fuels.

Combustor blowout at idle conditions occurred at a fuel/air ratio below 4.5 g/kg with all test fuels. Ignition tests were also conducted with variable-geometry combustor Configuration V-7 at altitude relight conditions. Light off could not be obtained at subatomspheric conditions, although both combustor inlet pressures and fuel flows were increased to promote ignition. Additional development effort will be required to determine whether this ignition problem is due to poor fuel atomization or fuel distribution at the subatmospheric relight condition or if ignition characteristics can be improved by changing the position of the ignitor.

Two potential failure modes of interest for the variable-geometry combustor concept are failure of the variable vane actuation mechanism in the fully closed or fully open positions.

For failure in the fully closed position, operation at idle would be normal, but swirler flow would be reduced at high power, increasing combustor pressure drop. This failure mode was simulated in Configuration V-7 by operating at the takeoff fuel/air ratio (22.8 g/kg) with the variable vanes open. Combustor inlet pressure and temperature were reduced to 0.27 MPa and 613 K, respectively, to ensure that the combustor would not

be damaged. Additional data were obtained at the same inlet temperature at a lower fuel/air ratio, with the vanes in both the open and closed positions. Data obtained at these three conditions are compared in Table 6-6. Combustor performance appears to be marginally acceptable during operation at the higher fuel/air ratio with the vanes closed, although the severity of operation in this mode would be increased at high inlet pressure and temperature. Liner temperature differentials were far below the program goals at the inlet condition tested and would not be expected to be a problem at true takeoff conditions. Combustor pressure drop was increased but was acceptably close to the program goal. Combustion efficiency was reduced slightly due to increased CO from the rich primary zone, but the measured levels would be acceptable for short-term operation. Smoke levels were also increased, but visible smoke would also be acceptable for short-term operation in case of an actuation failure. Based on detailed combustor exit profiles measured with vanes open and closed (Figure 6-65), operation would not be limited by exit temperature.

For the second failure mode of interest, failure with the vanes in the fully open position, high power operation would be normal, but idle operation would be of concern due to the swirler flow levels. Limited operation at idle inlet conditions with the vanes open was conducted with Configuration V-6. Stable operation was obtained at a fuel/air ratio down to 15.7 g/kg. At that condition, measured combustion efficiency was below 90% and was decreasing as fuel/air ratio was reduced. The actual blowout fuel/air ratio was not recorded, but it is unlikely that stable operation could be maintained at the true idle fuel/air ratio of 10.7 g/kg.

From these tests, failure in the vanes' closed mode appeared to be acceptable in that a full, or nearly full, range of operation could be obtained. With the vanes failed open, combustor blowout during deceleration to conditions near ground idle would probably occur. Therefore, the variable geometry should be implemented in such a way that the vanes would close in the event of an actuation or control system failure.

Table 6-6. Demonstration of High Fuel/Air Ratio Operation With Variable Vanes Fully Closed.

- Configuration V-6
- ERBS 12.8 Fuel

Operating Conditions	Value		
Vane Position, % Open	0	0	100
Fuel/Air Ratio, g/kg	22.8	11.9	11.9
Inlet Temperature, K	613	614	610
Inlet Pressure, MPa	0.27	0.56	0.55
Operating Characteristics			
$T_{Liner} - T_3$, K			
Average	82	67	50
Maximum	145	100	85
Corrected Combustor Pressure Drop, %	6.3	5.8	4.8
Corrected Combustion Efficiency, %	98.2	99.8	98.7
Smoke Number	11.3	7.1	4.6

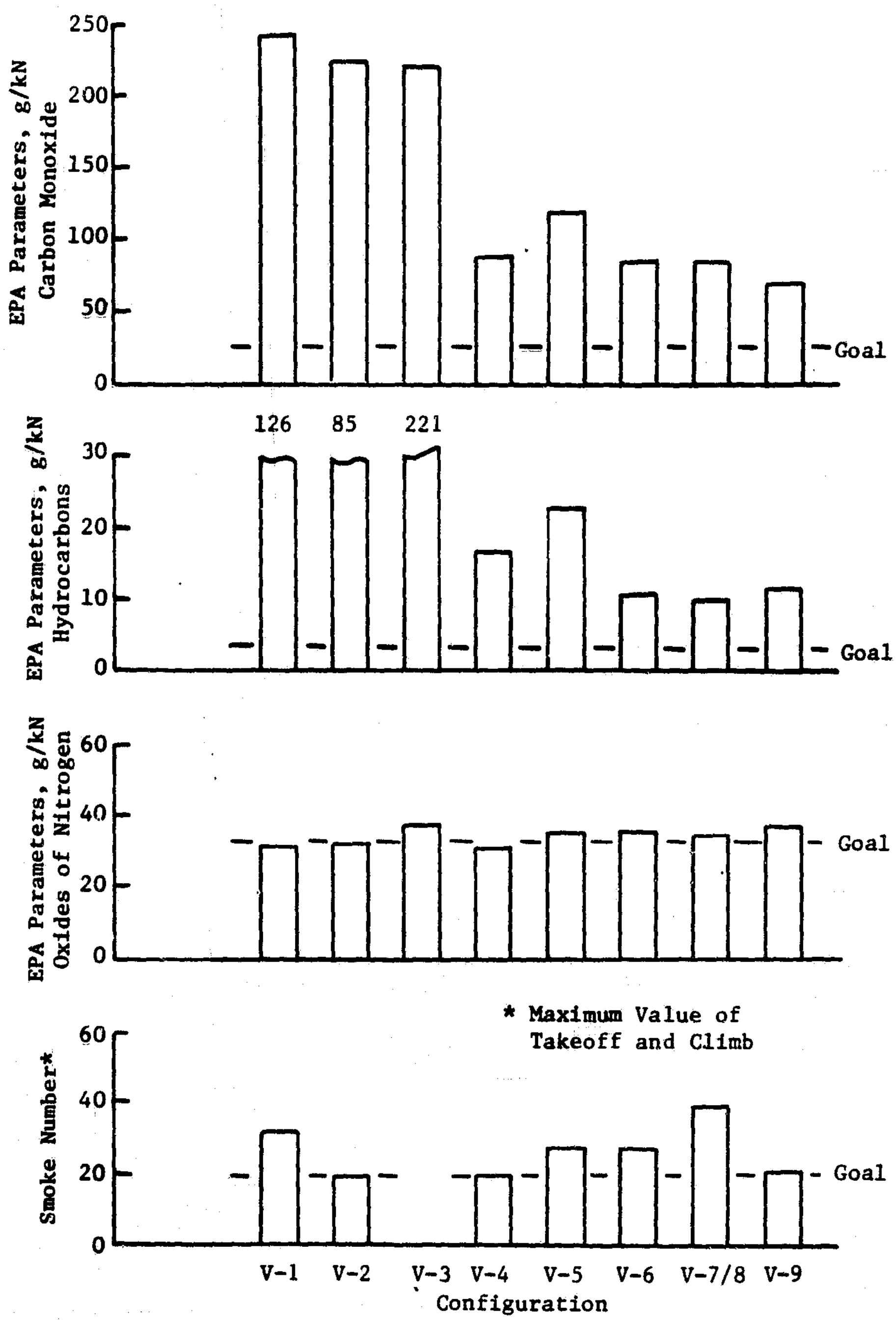
6.3.2 Combustor Development Progress

The baseline variable-geometry combustor demonstrated ultra-low combustor liner metal temperatures, a low idle blowout fuel/air ratio, and combustor pressure drop levels which closely approached the design values. Emissions of NO_x met the program goal, and the variable-geometry feature of this combustor was actuated without any problem. Tests of this baseline variable-geometry combustor configuration did, however, indicate the need for significant improvement in combustion efficiency (and reductions in associated CO and HC emissions) throughout the combustor operating range and a less critical need to reduce smoke emissions. Combustor exit temperature profiles also needed considerable improvement, but this area was considered to be more appropriate for later development efforts. Therefore, a majority of the modifications to this concept, which have been described in detail in Section 4.2.3, were directed toward increasing combustion efficiency, with a secondary emphasis on the reduction of smoke emissions.

6.3.2.1 Emissions

Emissions results obtained with the nine different variable-geometry combustor configurations are compared in Figure 6-67. Configuration V-1 and V-2 EPA parameter values were calculated based on operation with the variable vanes open at the approach power level. This mode was appropriate because combustor pressure drop levels for these two configurations with the variable vanes closed were in the 7% to 8% range, which is higher than the desired level of 6%. In subsequent configurations, pressure drop was 6% or below with the vanes closed so operation in this mode at the approach power level was appropriate. Since Configuration V-9 was a fixed geometry simulation of the combustor with the variable vanes in the open (high power) position, low power operation was not evaluated. EPA parameters for this configuration were therefore calculated using idle and approach power emission levels measured with Configuration V-7.

Baseline CO and HC emissions were well above the program goals. Slight reductions in these levels were obtained by the addition of primary



Note: EPAPS are Based on Operation with the Vanes Closed at the Approach Condition Except for Configurations V-1 and V-2.

Figure 6-67. Variable-Geometry Combustor Emissions.

dilution in Configuration V-2. The use of compensating dilution in Configuration V-3 to decrease idle pressure drop, thereby reducing cooling film flows which can quench CO and HC, was not effective in reducing CO levels. HC emissions actually increased with this modification, probably due to a deterioration in fuel atomization with reduced pressure drop.

A very significant reduction in CO and HC was obtained by incorporating a primary venturi extension into Configuration V-4 (as described in Figures 4-21 and 4-22). This modification reduced CO emissions by about 65% and HC emissions by about 90% at the idle operating conditions. As shown in Figure 6-68, the airflow distribution modifications incorporated into this configuration also shifted the CO and HC emissions so that the minimum CO levels were obtained at the design point fuel/air ratio. With Configuration V-4, CO and HC levels of 65 and 15, respectively, are in the same range as double-annular emissions status at a similar stage of development (42 g/kg CO and 10 g/kg HC) after tests of six double-annular configurations in Phase I of the NASA/GE Experimental Clean Combustor Program.

Reduced dome and forward liner cooling flows in Configuration V-5 were ineffective for CO and HC emissions reduction and, in fact, these emissions increased. Other significant reductions in both CO and HC emissions were obtained by using the simplex fuel nozzle tip design which was incorporated into Configuration V-6 (shown in Figure 4-23). This fuel nozzle modification alone resulted in a one-third reduction in CO emissions and a reduction of more than 50% in HC.

Configuration V-9, with its radically different swirler and low pressure injectors, provided a slight reduction in CO levels at high power. Operation at idle, where CO and HC emissions are most important, was not evaluated in this configuration since this was a fixed-geometry simulation in which the swirl vanes could not be closed for low power operation.

Throughout the variable-geometry combustor test series, NO_x levels were close to the program goal. Combustor modifications having a very strong effect on CO and HC emissions levels had virtually no effect on

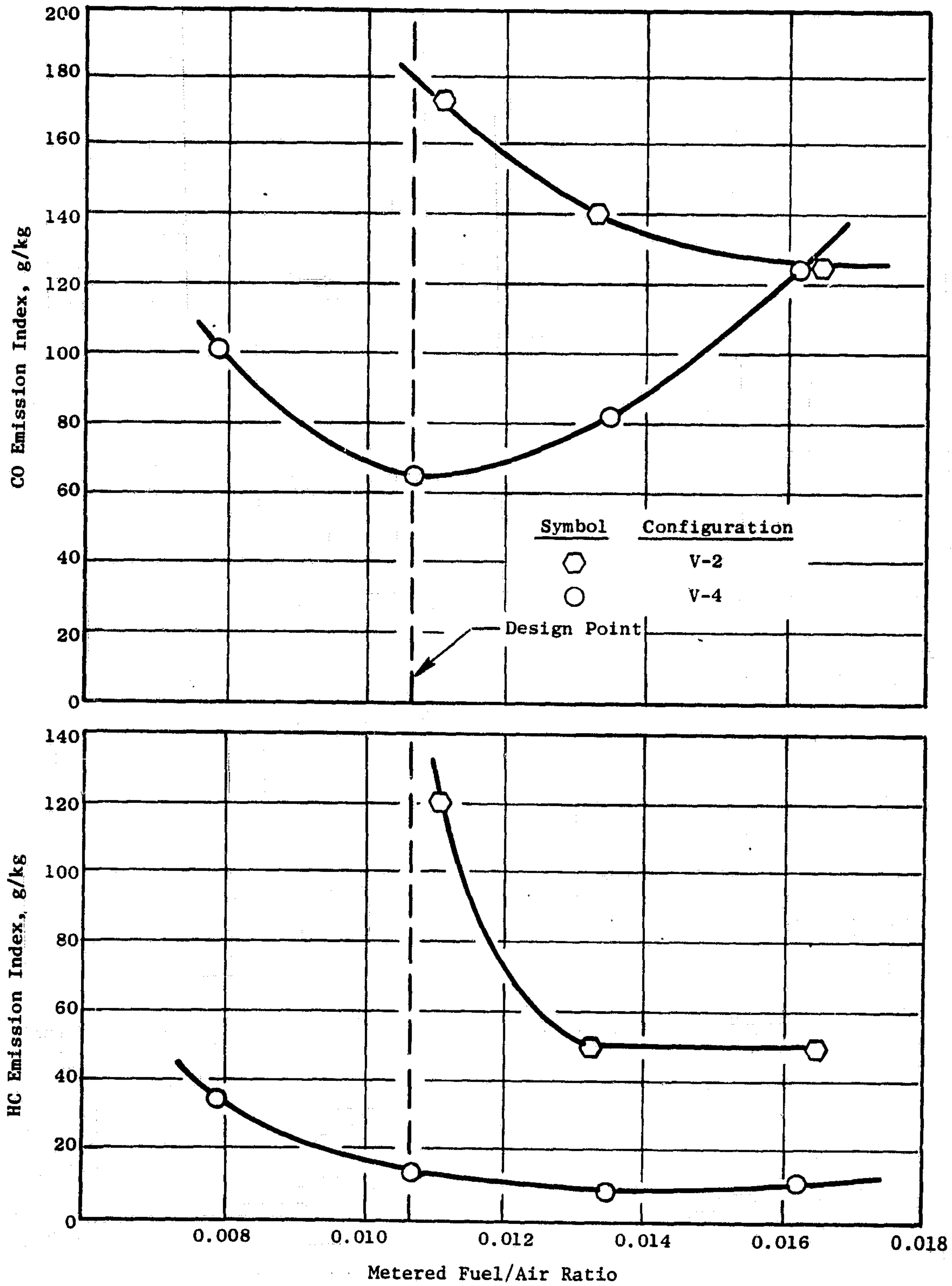


Figure 6-68. Variable-Geometry Combustor Idle Emissions Comparison (4% Idle).

NO_x. Even the reduced authority variable-geometry modification, which increased the effective primary zone equivalence ratio at takeoff from about 0.6 to about 0.8, had little effect on NO_x emissions. The slight increase in NO_x levels obtained in Configurations V-3 through V-8 is due largely to increased NO_x emissions at the approach power level for operation with the variable vanes closed. NO_x emissions from Configuration V-9 were remarkably similar to the other variable-geometry combustor configurations, in spite of significant changes in several of the design variables (swirlers, fuel injectors, flow splits, and velocities).

Configurations V-2, V-8, and V-9 each had one or more modifications intended primarily for smoke reduction. However, other modifications also affected smoke emission. Primary dilution incorporated into Configuration V-2 reduced smoke emissions to levels below the program goal. Configuration V-3 was aimed primarily at low power operation, and meaningful high power smoke data were not obtained. In Configurations V-1 and V-2, smoke data were not well ordered as in conventional combustors. There was a good deal of data scatter, and no clear variation in smoke number was observed with changes in power level. In these first three configurations, maximum smoke levels with the ERBS 12.8 fuel were measured at the climb operating condition, whereas maximum smoke is generally obtained at the highest power level. It is thought that this anomalous behavior was due to an instability in the fuel spray pattern of the baseline variable-geometry swirl cup. Atmospheric pressure tests of this swirl cup revealed that under certain conditions the fuel spray could be stabilized in either of two distinct modes, having significantly different spray distributions. Smoke formation would then depend on the spray mode of each of the combustor swirl cups.

In Configurations V-4 through V-8, which incorporated a primary swirler venturi extension to stabilize the fuel spray, the smoke data were well ordered. These configurations also had reduced swirler flow, which would tend to increase smoke formation. Configurations V-4 through V-6 had smoke levels of about 19 at climb. V-5 and V-6 had a smoke level of

26.5 at takeoff (V-4 was not evaluated at takeoff conditions). Configurations V-7 and V-8 incorporated a slight increase in primary dilution and high pressure simplex fuel nozzles for improved atomization. Both of these modifications were incorporated with the objective of reducing smoke emissions. However, smoke levels were actually increased, probably due to some as yet undetermined characteristic of the fuel spray distribution with the simplex fuel nozzles.

Interpretation of smoke data obtained with Configuration V-9 is difficult because several of the sampling rake elements were damaged before smoke samples were obtained. However, the limited data obtained indicate that smoke levels were still above the goal with this configuration. This was unexpected in that the same swirler configuration used in Configuration V-9 had demonstrated low smoke levels in a previous test program. This suggests the need for further study of the effect of interactions between the dome, primary dilution jets, and swirl cups on smoke emissions in this combustor concept.

In summary, good progress has been made in reducing CO and HC emissions in the variable-geometry combustor concept, without significantly affecting NO_x levels. Substantial further development of this combustor concept will be required to meet CO and HC goals, and additional smoke emissions reduction is also needed, but no barrier problems have been revealed. It is known that the basic dome velocities and stoichiometries with this concept are appropriate to the obtaining of low emission within the reference engine cycle operating conditions. With additional development to define details of the variable swirl cup and dome assembly, this concept should be capable of meeting all of the program emissions goals.

6.3.2.2 Performance

Variable-geometry combustor performance progress is summarized in Figure 6-69. Except for combustion efficiency, which is related to CO and HC emissions and exit temperature profiles, the variable-geometry combustor easily met all of the program steady-state performance goals.

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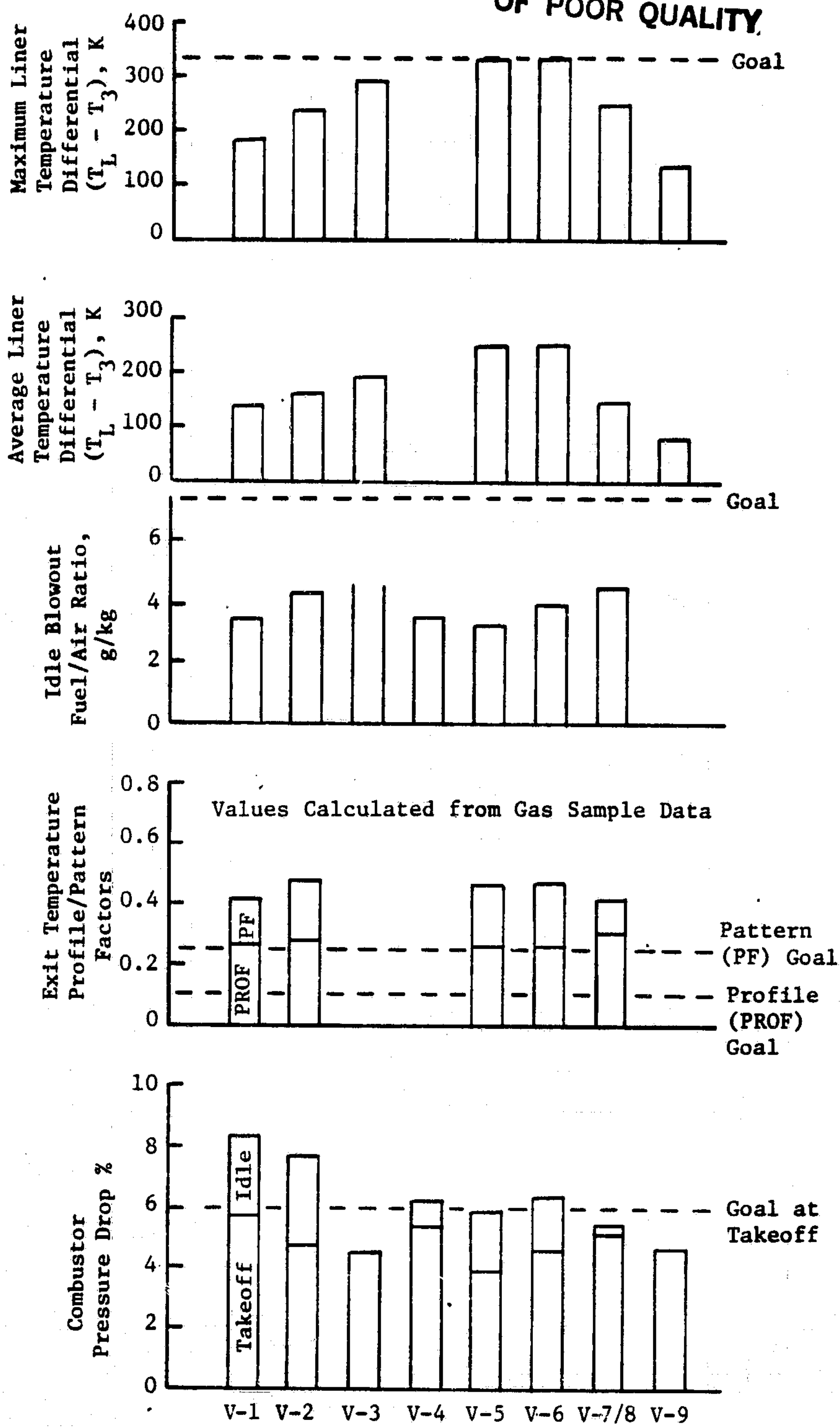

Figure 6-69. Variable-Geometry Combustor Performance.

Combustor liner temperatures, which were very low in the variable-geometry combustor baseline configuration, were increased in Configurations V-2 through V-6, as swirler airflow and liner cooling levels were reduced for emissions reduction. In Configurations V-7 and V-8, liner temperatures were reduced by reinstating a portion of the liner cooling flow and using thermal barrier coatings. Very low liner temperature levels were obtained in Configuration V-7 through the use of increased cooling flow levels with impingement/film cooling of the combustor liners.

The idle blowout fuel/air ratio was very low for all of the variable geometry configurations. No attempt was made to improve idle blowout characteristics. Combustor exit profile and pattern factors were above the goal levels for all of the variable-geometry combustor configurations and were not strongly affected by the combustor modifications evaluated in this program. Significant improvements in primary zone uniformity, which are needed for smoke emissions reduction in this combustor concept, should also improve the exit temperature profiles. Profile trim would be a consideration in later development efforts with this combustor concept.

The primary modification affecting combustor pressure drop was the use of limited authority variable-geometry in Configuration V-4 and subsequent configurations. For these configurations, pressure drop met or closely approached the program goal of 6% with the variable vanes closed. Combustor pressure drop was below the program goal at takeoff for all of the variable-geometry combustor configurations.

Combustion efficiency at idle was increased from a level of about 92% in the baseline configuration to more than 97% in Configurations V-4 and V-7, based on measured CO and HC emissions. At approach conditions, combustion efficiency was increased to 99.8% with the variable vanes closed and 98.7% with the vanes open, compared to values of 99.0% and 91.4%, respectively, in Configuration V-1.

Significant carboning occurred on the inner surface of the swirler venturi extension in Configuration V-8 (Figure 6-66). However, this carboning occurred only with the high pressure, simplex fuel nozzles used in that configuration. Inasmuch as these nozzles were ineffective for smoke

reduction, they would not be used in future configurations of this combustor concept. Therefore, the observed carboning would not be expected to occur again.

In summary, during this Phase I test program, significant improvement in combustion efficiency performance was obtained with the variable-geometry combustor. Additional development effort will still be needed to improve the exit temperature profiles obtained with this concept. Other aspects of steady-state performance met the program goals. Also, as indicated in the previous section, further altitude relight development will be required. Based on the low idle blowout fuel/air ratios measured in these tests, the ultimate altitude relight potential of this concept is high.

6.3.3 Fuel Effects

Five of the nine variable-geometry combustor configurations tested in this program were evaluated with all four of the test fuels. Fuel effects on combustor emission and performance observed in these tests are discussed below.

6.3.3.1 Emissions

Carbon monoxide emissions from the various variable geometry combustor configurations are shown as a function of fuel hydrogen content at three different power levels in Figure 6-70. Configuration V-1 CO emissions at idle are not shown because the levels were above the range of practical interest, so data were not obtained on all four fuels. With all of the variable-geometry configurations shown, CO tended to increase at the idle and cruise conditions as fuel hydrogen content was reduced. No consistent trend was observed at the takeoff operating condition. This figure also shows that CO levels at the high power levels were significantly reduced relative to the baseline combustor in Configurations V-5 and V-8. Based on the best-fit lines of CO as a function of fuel hydrogen content, idle CO levels were only increased by about 3% in Configuration V-6 and by about 6% in Configuration V-7, for a reduction from 14% to 13% fuel hydrogen content. Similar effects (less than 10% increase in CO)

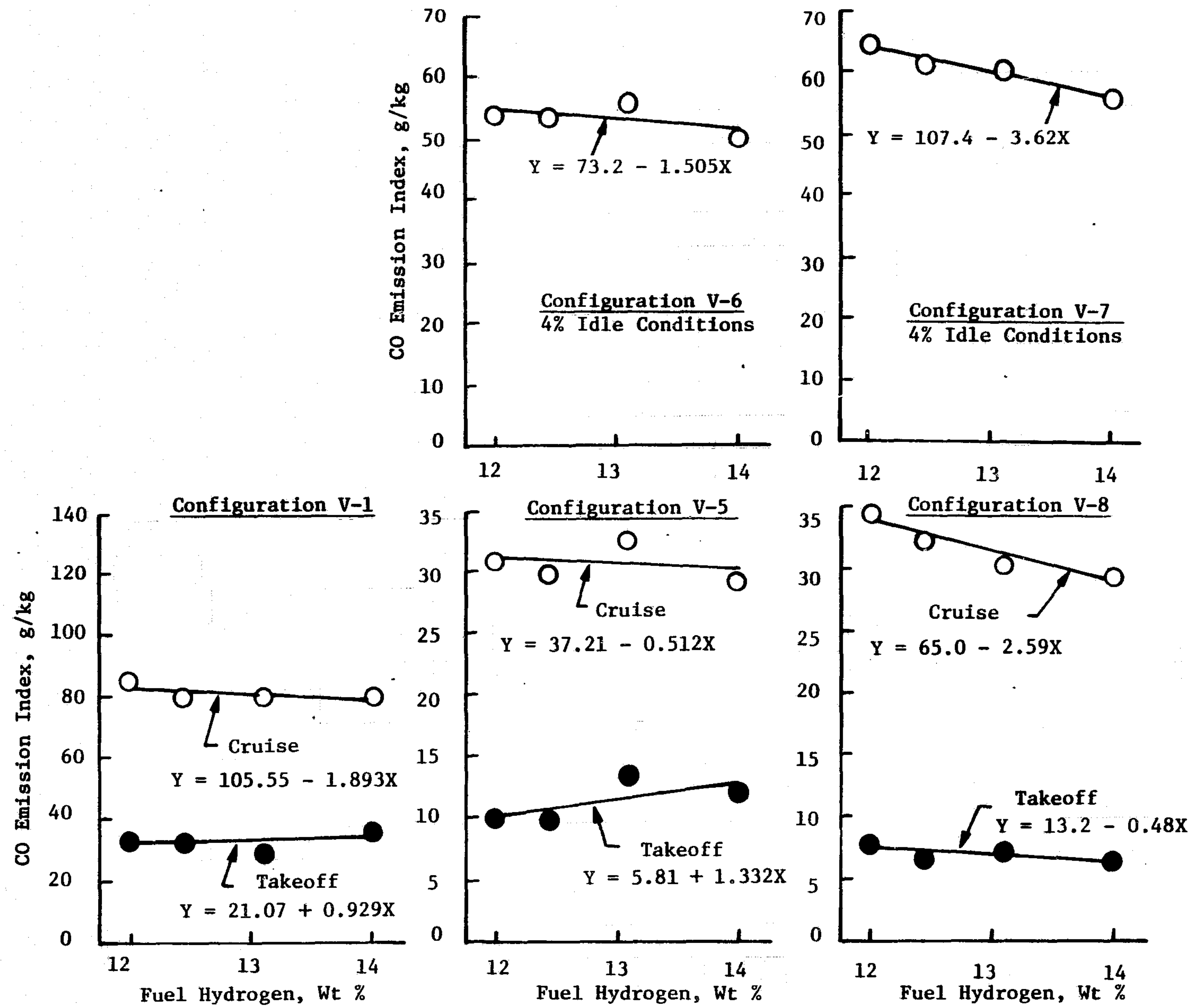

Figure 6-70. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor CO Emissions.

were observed at cruise conditions. Thus fuel properties do not have a major effect on CO emissions.

The effect of fuel properties on HC emissions is shown in Figure 6-71. Again, HC levels are significantly reduced in the later configurations. As with CO, HC tended to increase with decreasing fuel hydrogen content at the idle and cruise conditions. The fuel effect on HC was slightly stronger than on CO, but the increase in idle HC level was still less than 10% for a reduction from 14% to 13% fuel hydrogen content.

Although CO and HC emissions have been shown as a function of fuel hydrogen content in Figures 6-70 and 6-71, the observed effects are probably due at least in part to physical properties (viscosity, surface tension, volatility) of the test fuels. Since the physical properties tended to vary with hydrogen content in the test fuels used, it was not possible to separate the physical effects from the chemical effects.

Figure 6-72 shows NO_x emission indices for the variable-geometry combustor configurations as a function of fuel hydrogen content. Both NO_x levels and fuel effects were similar for all of the configurations tested. NO_x emissions were increased by an average of slightly more than 6% for a one-point reduction in fuel hydrogen content.

The effect of variation in fuel hydrogen content on variable-geometry combustor smoke emissions is shown in Figure 6-73. In all configurations and at all power levels, smoke levels were found to increase rapidly as fuel hydrogen content was reduced. Based on best fit lines of smoke as a function of fuel hydrogen content for all of the configurations, smoke levels increased by an average of 89% at idle, 83% at cruise, and 46% at takeoff, for a reduction from 14% to 13% fuel hydrogen content. Sensitivity to changes in fuel hydrogen content (percent change in smoke for a one-point reduction in fuel hydrogen) was about the same for all of the configurations tested.

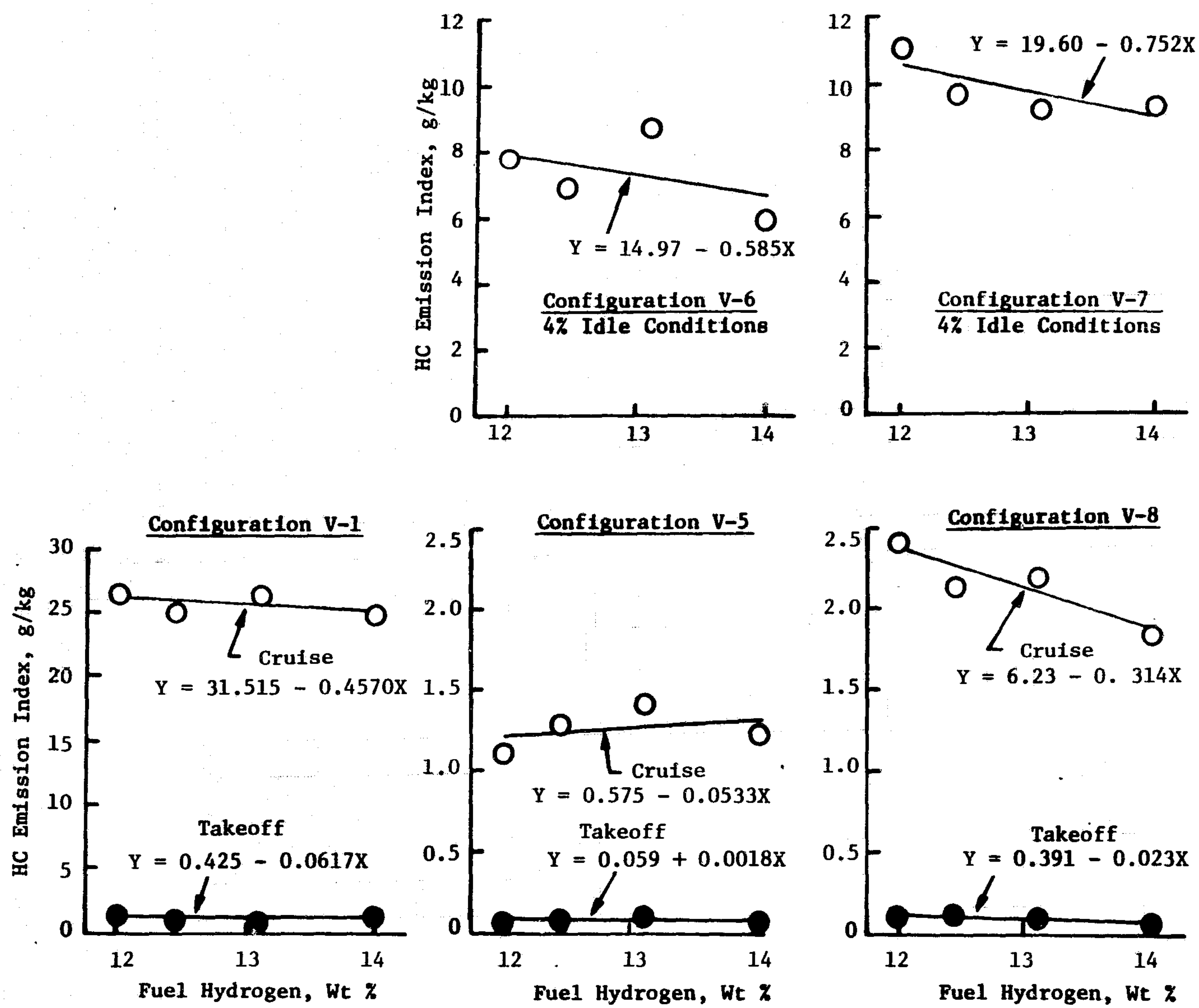

Figure 6-71. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor Unburned Hydrocarbon Emissions.

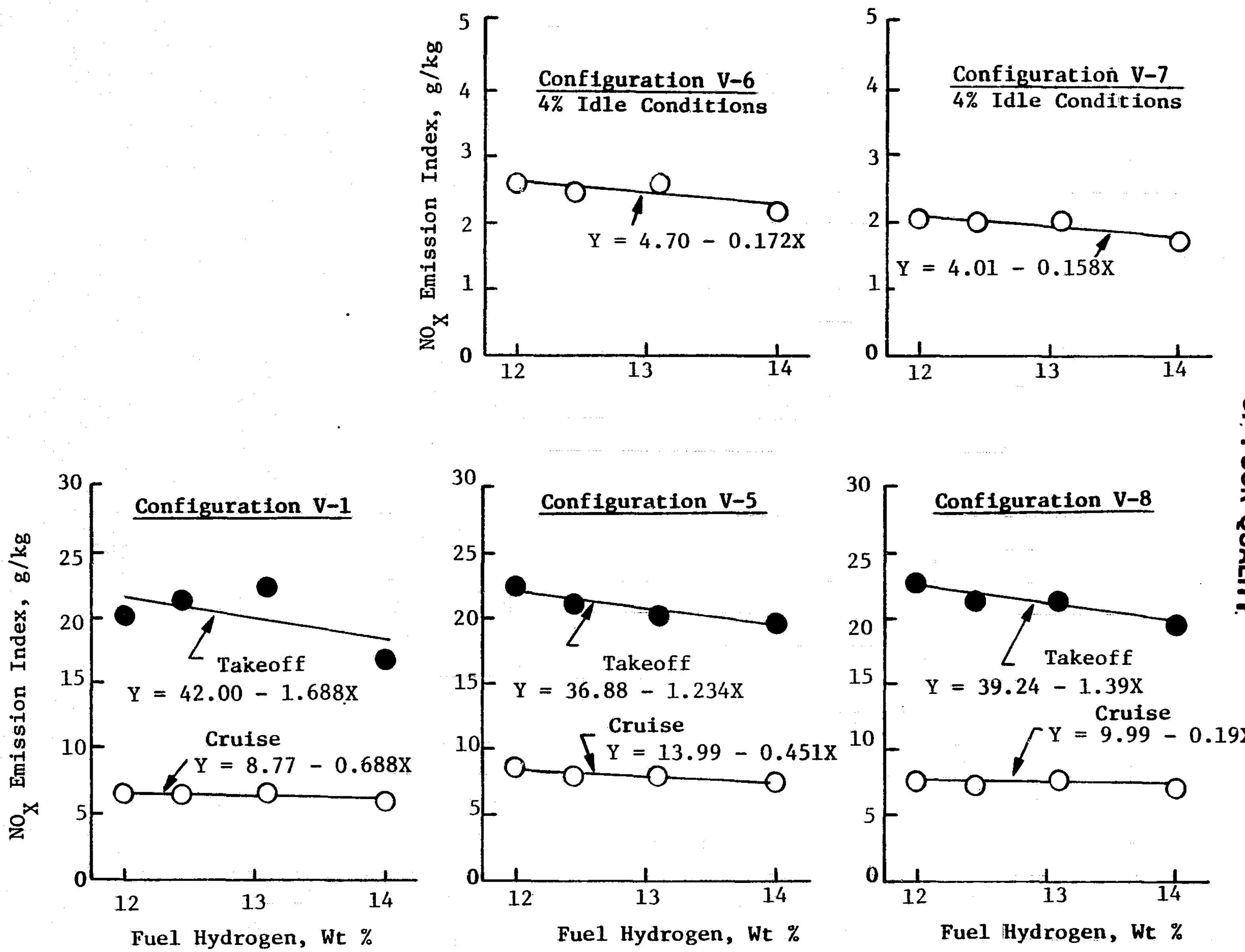

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Figure 6-72. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor NO_X Emissions.

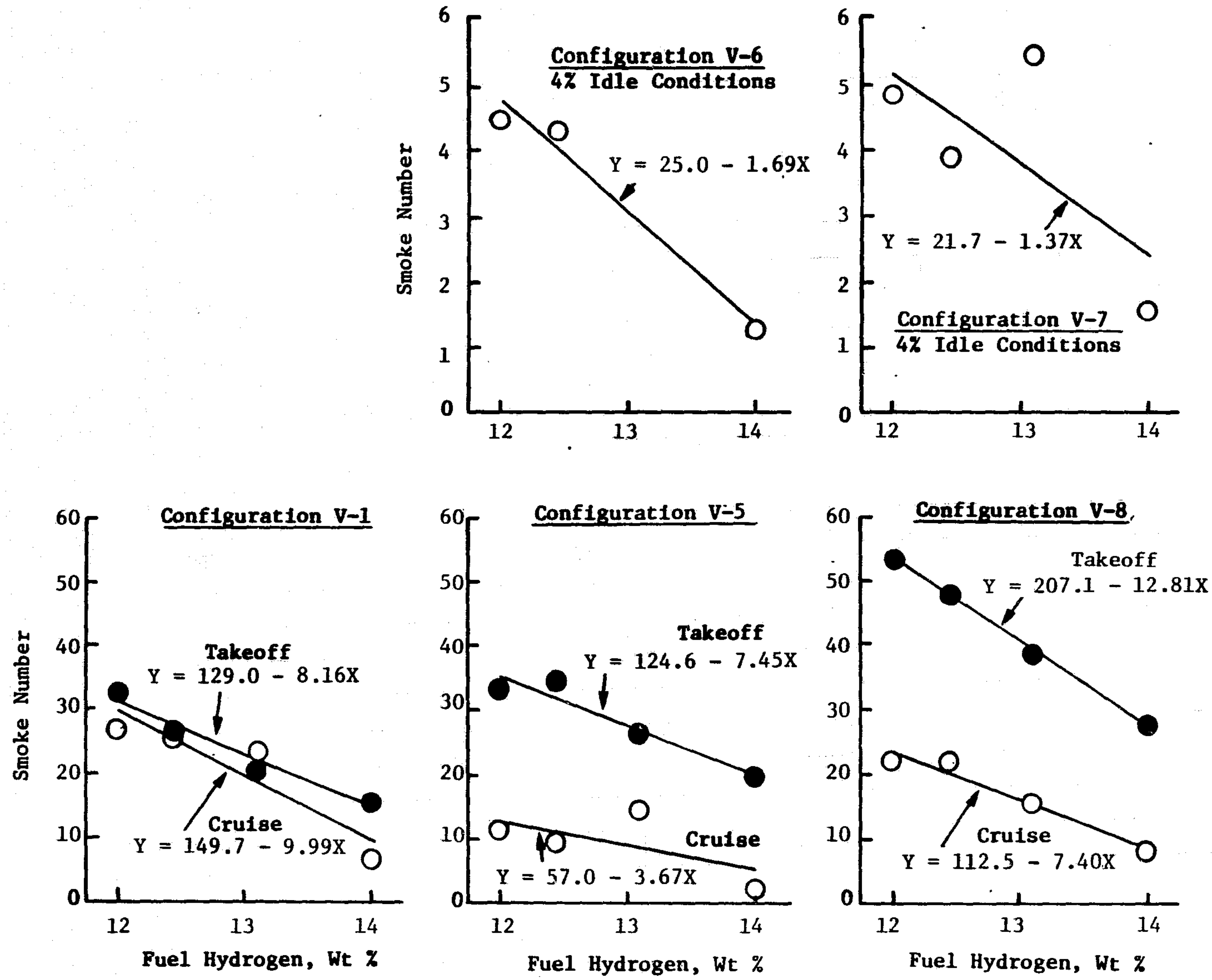

Figure 6-73. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor Smoke Emissions.

6.3.3.2 Performance

Variable-geometry combustor average and maximum liner temperature differentials at the idle, cruise, and takeoff operating conditions are shown as a function of fuel hydrogen content in Figures 6-74 and 6-75, respectively. As in the case of the double-annular combustor concept, liner temperatures of the variable-geometry combustor configurations were relatively insensitive to variation in fuel hydrogen content at idle conditions. However, the baseline variable-geometry combustor liner temperatures were quite sensitive to fuel hydrogen at high power conditions. At takeoff conditions, the baseline variable-geometry average liner temperatures were increased by over 12% when fuel hydrogen content was reduced from 14% to 13%. This was about the same percentage change obtained with the baseline configuration of the single-annular combustor; however, peak liner temperatures with the variable-geometry combustor were more than 90 K lower than with the single-annular combustor.

Liner temperature sensitivity (on a percentage basis) to changes in hydrogen content was reduced in Configuration V-5 by increasing convective heat transfer to the combustor liners (due to reduced film cooling). Since the radiation heat load did not change, the proportion of the total heat transfer to the liners due to convection increased. However, the absolute sensitivity (unit change in temperature per unit change in fuel hydrogen content) did not change relative to Configuration V-1 characteristics. For example, a one-point change in hydrogen content resulted in a 15 K change in the average liner temperature and a 20 K change in maximum liner temperature at takeoff conditions for both Configurations V-1 and V-5. Obviously, the liner temperature characteristics of Configuration V-5 were inferior to the baseline configuration even though percent change in liner temperature was reduced.

In Configuration V-8, absolute liner temperatures were reduced to about the same level as in the baseline configuration, but liner temperature sensitivity was reduced. This reduced sensitivity is apparently due primarily to the use of thermal barrier coatings in this configuration,

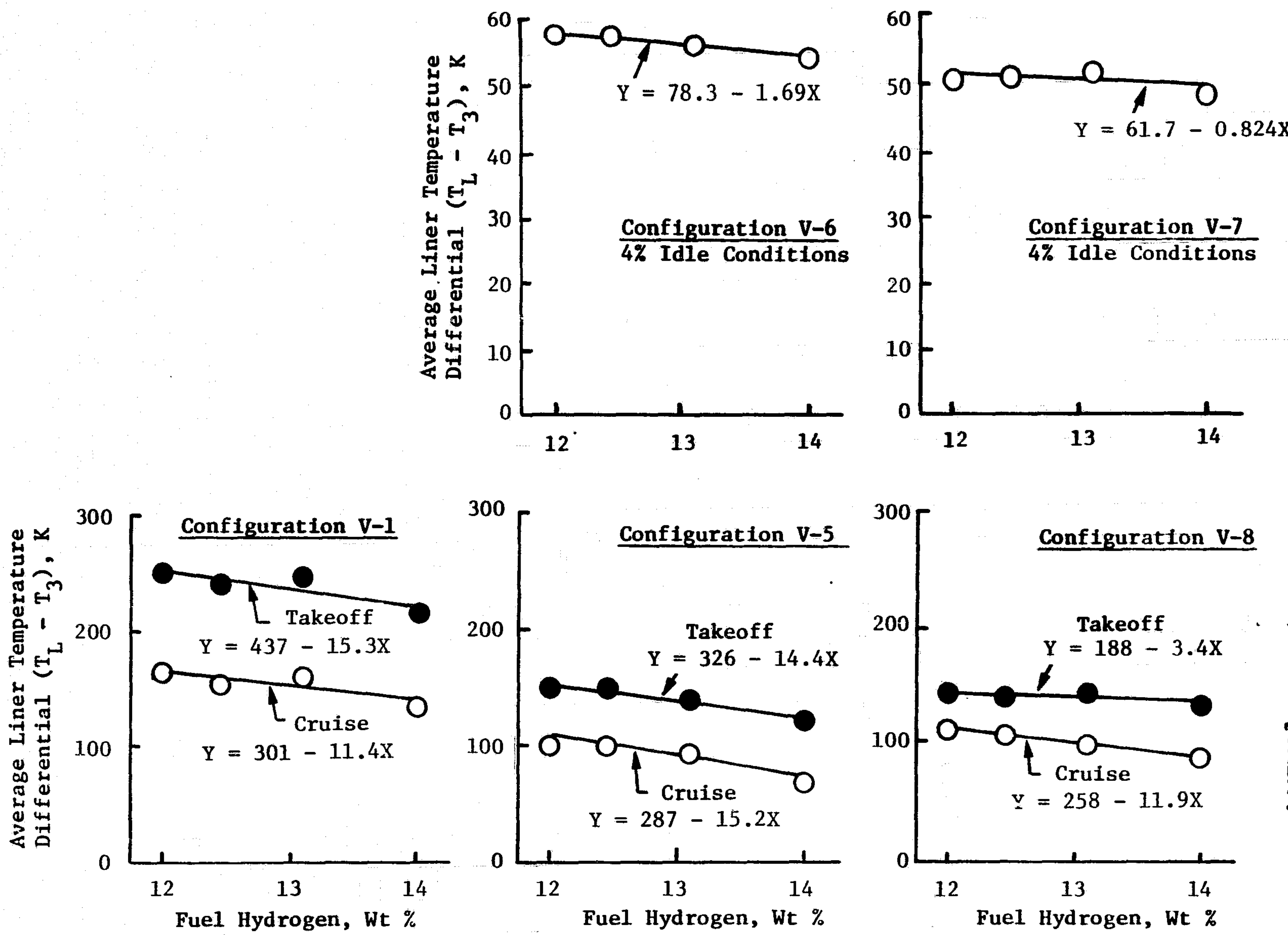

Figure 6-74. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor Average Liner Temperatures.

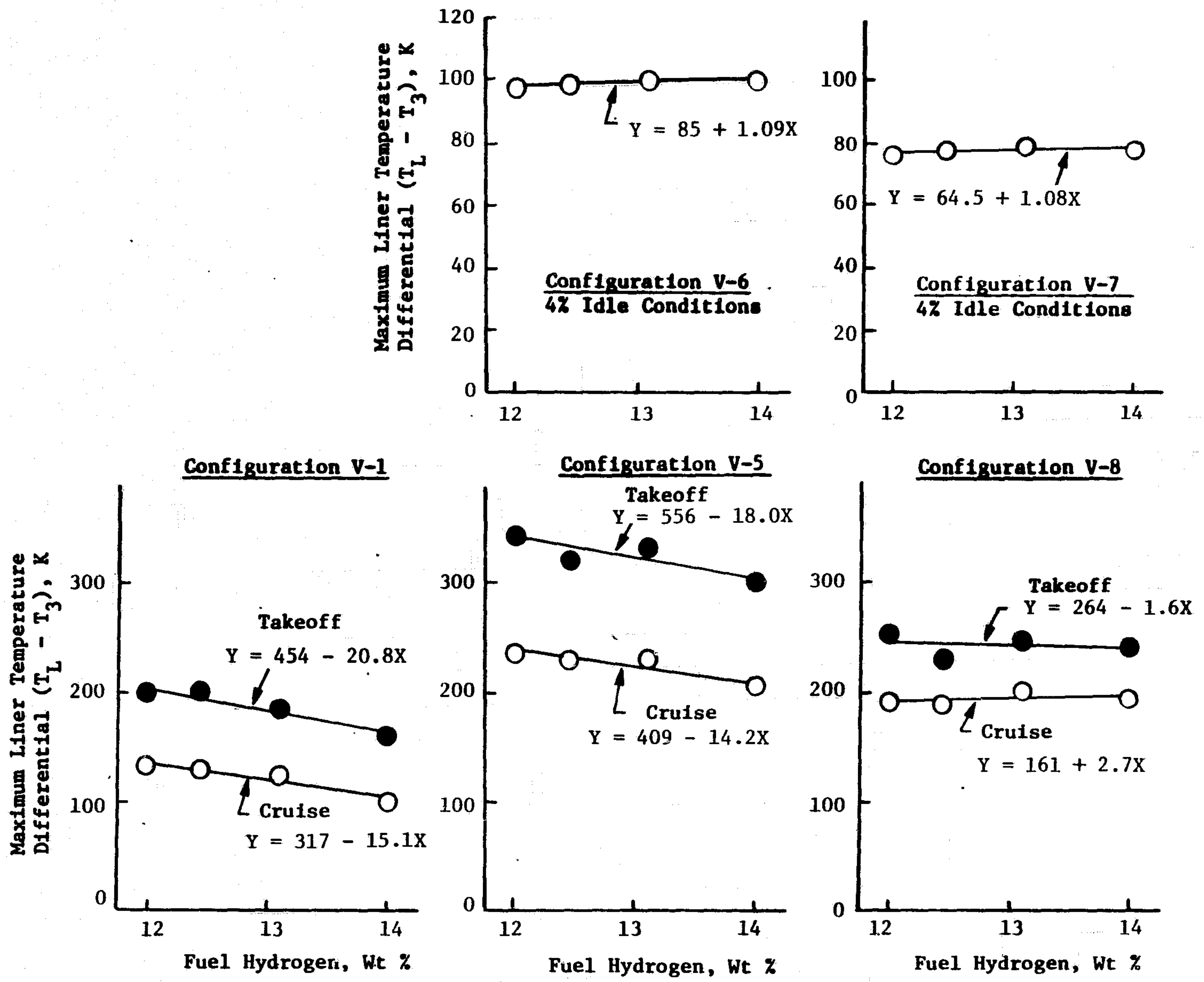

Figure 6-75. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor Maximum Liner Temperatures.

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since there is no reason to believe that the radiative heat load was reduced in this configuration (as shown in Figure 6-73, smoke levels were actually increased, indicating a probable increase in radiation). As shown in Figure 6-76, radiant heat flux did increase as fuel hydrogen content was reduced in tests of Configuration V-8.

The effects of increased flame radiation were apparent in forward panel liner temperatures of Configuration V-8, as shown in Figure 6-77. The first panel of the outer liner was particularly sensitive. However, the temperature measured on this forward panel was more than 100 K lower than the aft panel of the outer liner with all of the fuels tested. Therefore, this location was not life-limiting.

Profile and pattern factors of the variable-geometry combustor were virtually unaffected by fuel properties, as indicated in Figure 6-78.

Variable-geometry combustor blowout fuel/air ratios at idle conditions were not strongly affected by fuel properties (Figure 6-79). No altitude relight or blowout data were obtained with this combustor concept.

In summary, the only aspects of combustor performance which showed a definite effect of fuel hydrogen content were liner temperatures and associated flame radiation levels. A significant reduction in liner temperature sensitivity was obtained by the use of thermal barrier coatings. Even in the baseline configuration, where a strong liner temperature dependence on fuel hydrogen was observed, the effect was of minor concern because of the low liner temperature levels obtained.

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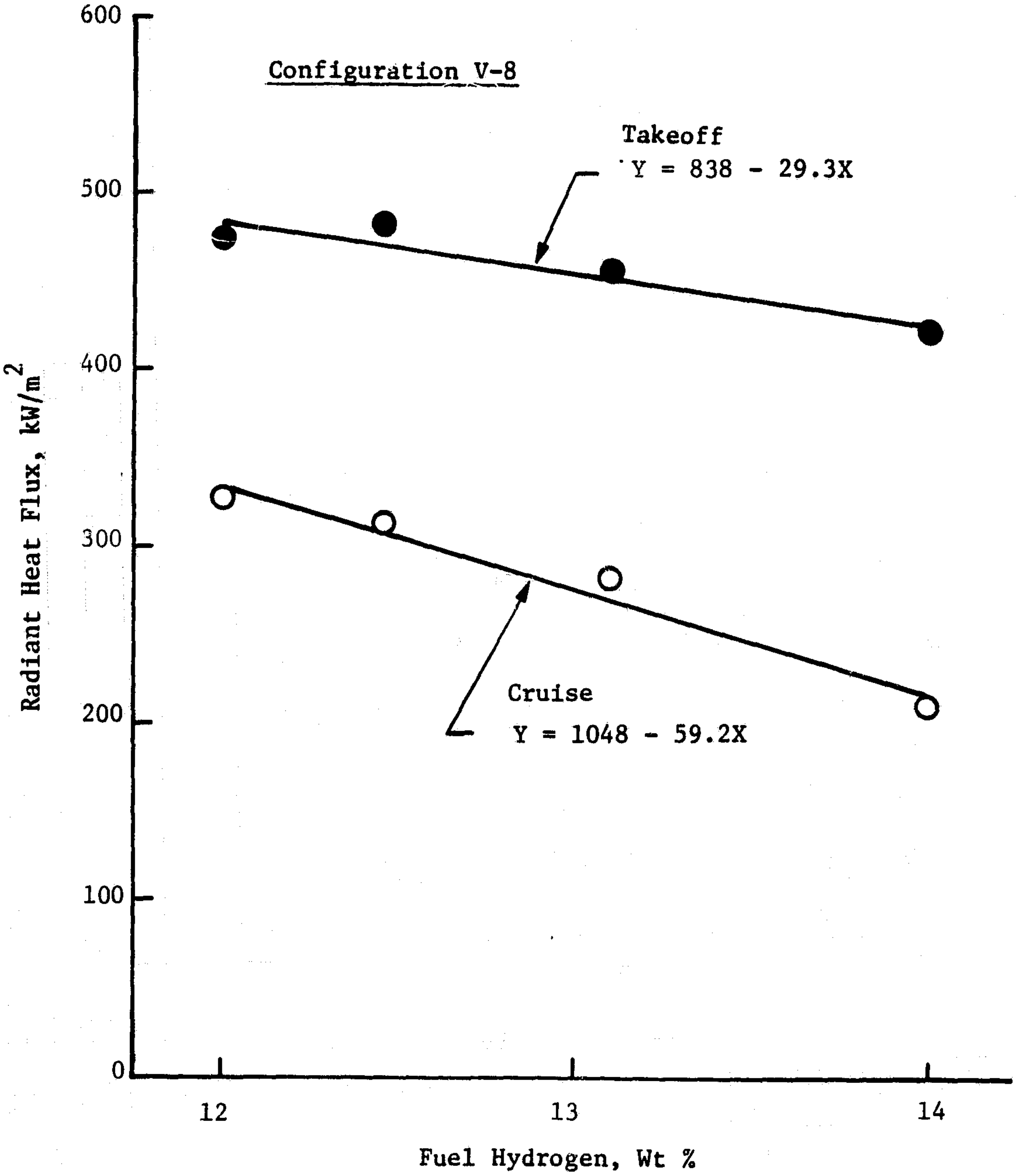

Figure 6-76. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor Radiation.

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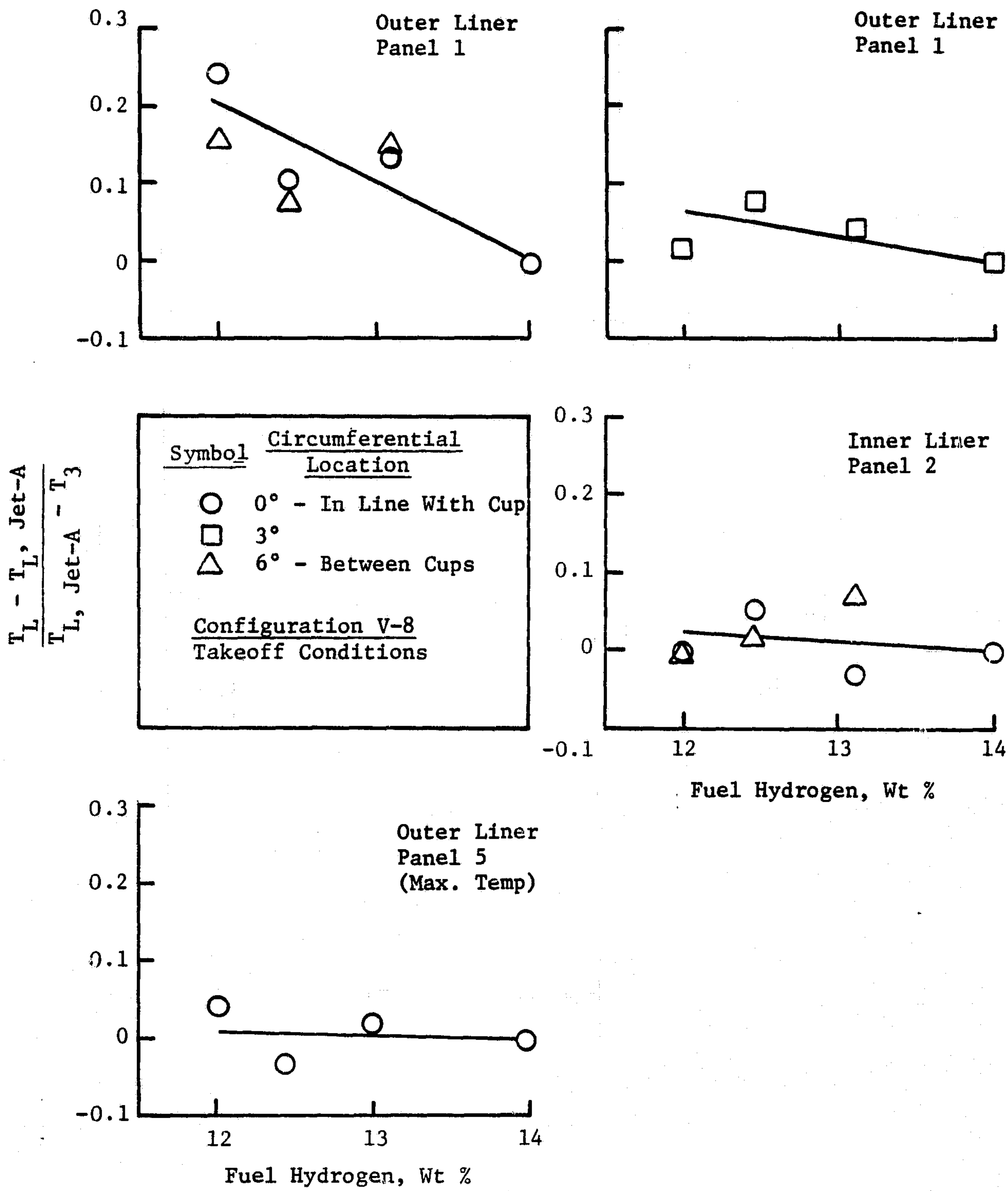

Figure 6-77. Effects of Fuel Hydrogen Content on Local Liner Temperature Parameter - Variable-Geometry Combustor Configuration V-8.

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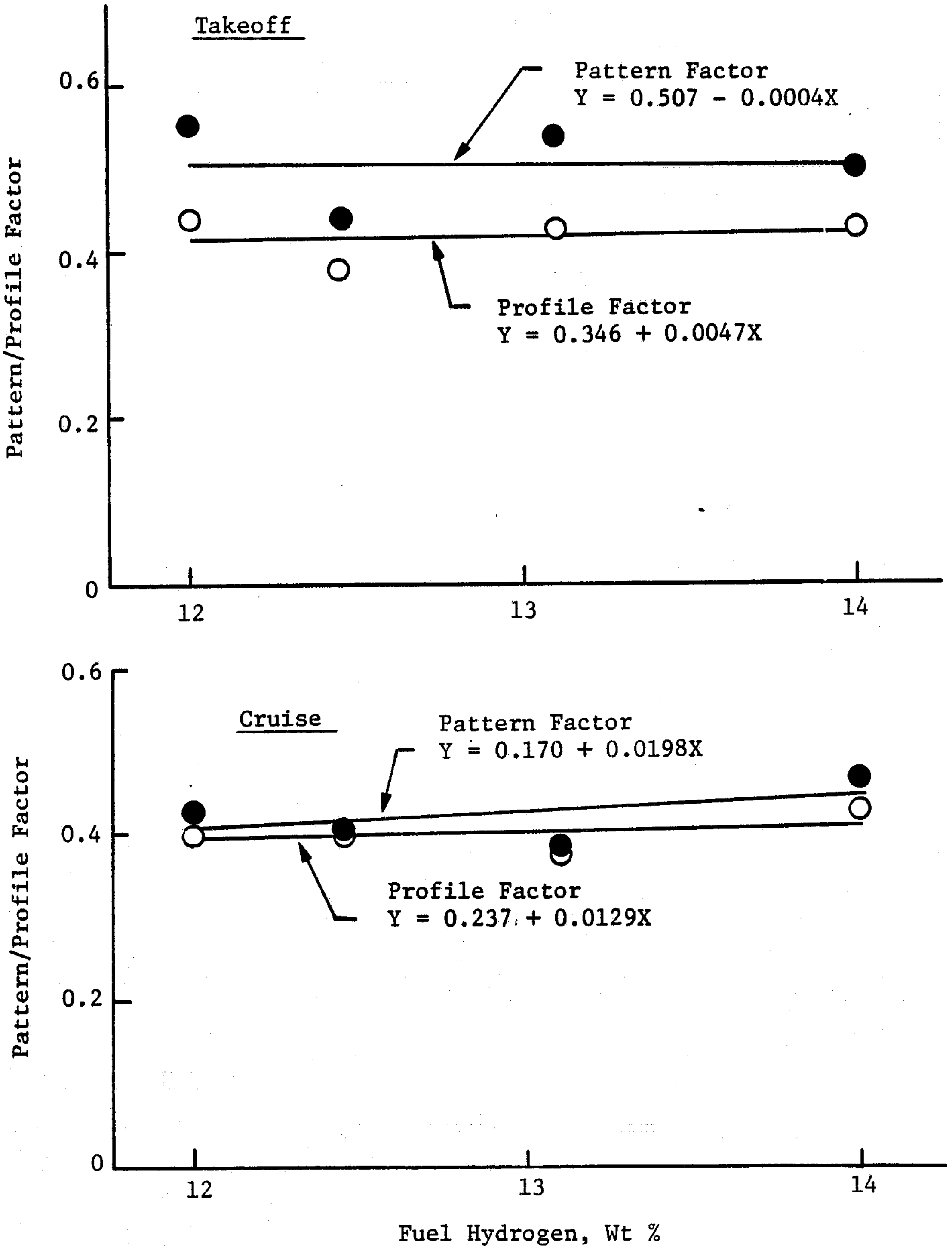

Figure 6-78. Effect of Fuel Hydrogen Content on High Power Exit Temperature Profile/Pattern Factor (Variable-Geometry Combustor, Configuration V-5).

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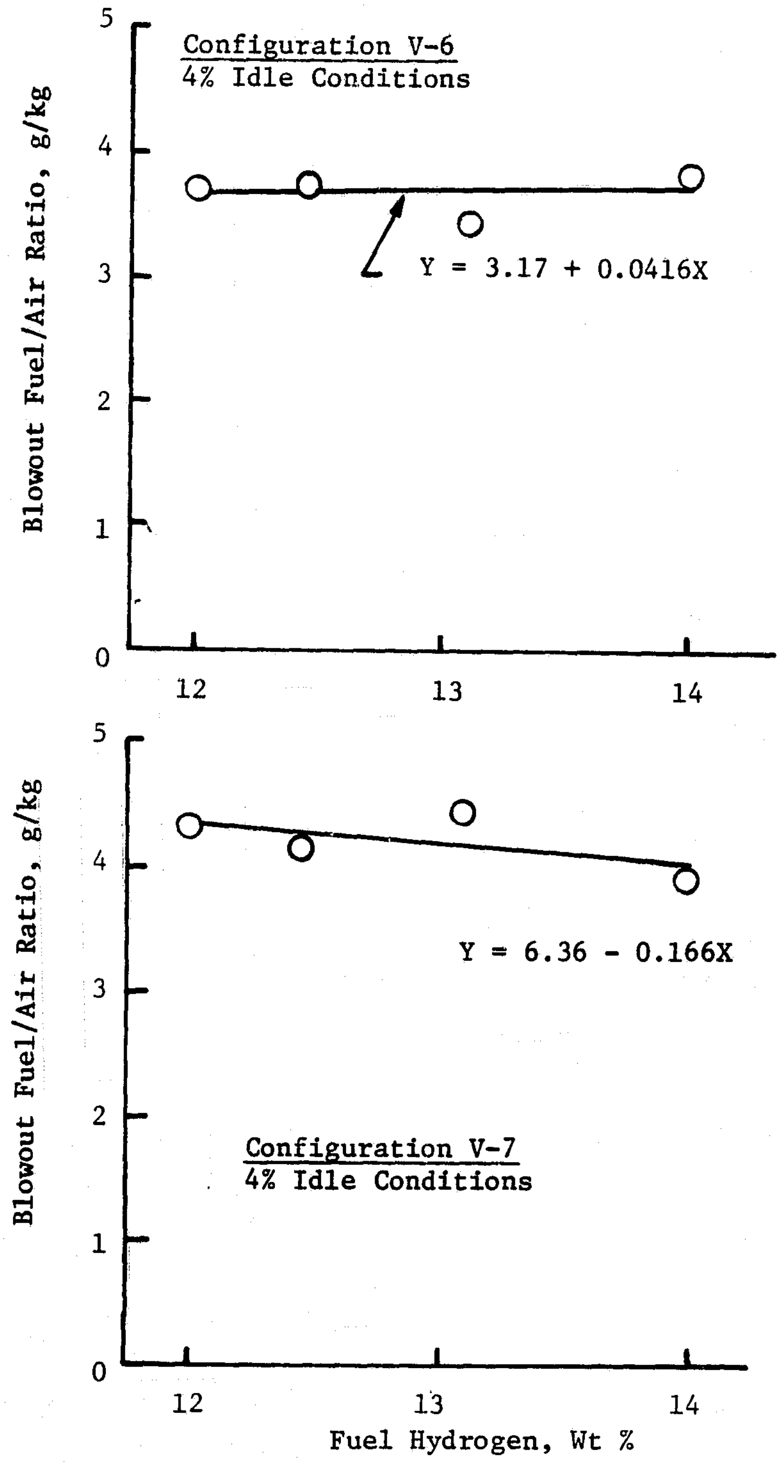

Figure 6-79. Effect of Fuel Hydrogen Content on Variable-Geometry Combustor Idle Blowout.

7.0 ASSESSMENT OF RESULTS

Objectives of this program were to develop the emissions and performance characteristics of the three candidate combustor concepts; to evaluate and, where possible, to reduce the sensitivity of the candidate concepts to changes in fuel hydrogen content; and finally, to select the two most promising combustor concepts (or, conversely, to eliminate the least promising) for operation on broadened-properties fuels. In the previous section, development of the individual concepts was discussed. In this section, the concepts are compared and the rationale for the selection of the single-annular and variable-geometry concepts is discussed.

The key emissions and performance characteristics obtained with each of the candidate combustor concepts are compared in Table 7-1. This table includes results obtained with both the baseline and final, or best, configurations of each concept to indicate development progress. Applicable program goals are also presented in this table to put the test results in perspective.

Very substantial emissions progress was made with all three concepts, particularly in idle emissions reduction. Based on the status as of the end of the test program, the single-annular combustor is the most favorable in that it provides the lowest CO and HC levels and also meets the smoke emission goal with a considerable margin. However, much of this advantage has been obtained through extensive development of this combustor design concept prior to this program. It is thought that the advanced concepts can meet all of the emission goals with development, while it is unlikely that the NO_x goal can be achieved with the single-annular combustor.

Each of the combustor concepts exhibited certain performance strengths and weaknesses. The single-annular combustor provided the best all-around performance, meeting or closely approaching all of the program goals. Again, this is an indication of the extensive development of this concept. The double-annular combustor demonstrated superior exit temperature pattern and profile factors, but liner temperatures were somewhat

Table 7-1. Comparison of Combustor Concept Development Progress and Status.

Parameter	VALUE WITH ERBS 12.8 FUEL							
	Program Goal		Single-Annular Combustor		Double-Annular Combustor		Variable-Geometry Combustor	
	Single Annular	Advanced Concepts	Baseline Test	Final Test	Baseline Test	Final Test	Baseline Test	Final Test
EPA Parameters[(a)], g/kN								
CO	36.1	25.0	49.0	19.6	83.7	35.9	243	82.5
HC	6.7	3.3	2.8	0.4	18.1	6.1	126	10.1
NO_x	35.3	33.0	46.9	60.4	27.6	35.1	30.7	34.7
Smoke Number	19.2	19.2	41.2	9.3	4.0	3.0	27.0	34.4
Combustion Efficiency (Min), %								
Idle	99.0	99.0	98.6	99.6	97.1	99.0	91.9	97.6
Approach[(b)]	99.0	99.0	99.9	99.9	90.8	94.9	99.0	99.6
Approach[(c)]	99.0	99.0	-	-	-	99.2	91.4	98.5
Pressure Loss (Max), %								
Idle	-	-	4.3	4.4	4.5	5.8	8.4	5.3
Takeoff	6.0	6.0	4.3	4.4	4.5	5.8	5.6	4.7
Pattern Factor[(d)] (Max at Takeoff)	0.25	0.25	0.33	0.29	0.41	0.19	0.42	0.42
Profile Factor[(d)] (Max at Takeoff)	0.11	0.11	0.20	0.15	0.20	0.09	0.27	0.31
Carboning	Light	Light	Light	Light	Light	Moderate On Pilot	Light	Moderate On Venturi
Liner Temperature (Max)	1135	1135	1136	1049	1151	1133	990	1053
Idle Blowout f/a, g/kg	7.5	7.5	4.2	6.4	4.1	4.7	3.4	4.5

Notes: (a) - 4/2 Fuel Staging at Idle in Single Annular; Pilot Stage Only at Approach in Double Annular; Vanes Closed at Approach in Final Variable Geometry Configuration.
(b) - Both Stages Fueled; Variable Vanes Closed
(c) - Main Stage Sector burning; Variable Vanes Open
(d) - Based on Local Temperature Calculated From Individual Gas Samples.

higher than those of the other concepts, and the intermediate power combustor efficiency was low when two-stage operation was employed. The variable-geometry combustor demonstrated very low liner temperatures, but additional exit temperature profile development is needed. Carboning observed in the advanced concepts was not serious and could be eliminated with appropriate modification to the fuel nozzle shrouds (carbon-free operation was obtained in at least one configuration of each concept).

Overall, emissions and performance results of all of the combustor concepts were promising. However, certain limitations have been noted in each concept:

- Single-Annular Combustor
  - Fuel nozzle staging is required to meet idle emissions/efficiency goals.
  - Concept is not capable of meeting NO_x goals.
- Double-Annular Combustor
  - Pilot-only operation or main stage sector burning is required at approach to meet emissions/efficiency goals.
- Variable-Geometry Combustor
  - Operation with the variable vane closed or partially closed is required at approach to meet emissions/efficiency goals.

The observed effects of changes in fuel hydrogen content on combustor emissions and performance are summarized in Table 7-2. Effects are expressed in terms of sensitivity, defined as the percent change observed in the parameter of interest for a one-point reduction in fuel hydrogen content. Results have been grouped by magnitude of the correlation coefficient obtained from regression analysis. In cases where the correlation coefficient was below 0.6, no sensitivity value is shown.

The strongest emission effect was increased smoke, which was particularly sensitive at low power levels. This effect was virtually eliminated at takeoff conditions in the final single- and double-annular

Table 7-2. Combustor Sensitivity to Fuel Hydrogen Content

Configuration	Condition	Sensitivity, %[a]							
		CO	HC	NO_x	Smoke	Radiant Heat Flux	Liner Temperature Differential[b] Avg	Liner Temperature Differential[b] Max	Blowout Fuel/Air Ratio
Single-Annular									
Baseline (S-1)	**Takeoff**	-10.9	--	5.5	--	--	8.6	10.1	--
	Cruise	- 0.5	--	8.9	60.6	--	26.8	10.5	--
Final (S-10)	**Takeoff**	(-18.2)	54.3	5.2	(-21.6)	(1.6)	4.4	(0.7)	--
	Cruise	--	--	4.9	--	17.4	8.5	1.3	--
	Idle	--	--	9.5	21.8	39.6	8.0	7.7	--
Double-Annular									
Baseline (D-2)	**Takeoff**	--	--	13.4	- 8.5	--	(1.6)	-3.7	--
	Cruise	--	--	(12.3)	--	--	(2.8)	(-3.2)	--
	Idle	9.5	--	14.0	99.6	--	(-4.7)	(-4.5)	--
Final (D-5/D-6)	**Takeoff**	--	--	(8.1)	(-9.0)	4.6	(1.4)	--	--
	Cruise	-15.4	--	10.6	--	4.5	2.6	10.1	--
	Idle	30.2	(20.2)	20.2	68.1	--	-4.6	-5.7	9.6
Variable-Geometry									
Baseline (V-1)	**Takeoff**	--	--	(9.0)	55.1	--	11.6	12.6	--
	Cruise	(2.4)	--	(2.6)	102.1	--	20.5	14.6	--
Intermediate (V-5/V-6)	**Takeoff**	(-10.4)	--	6.3	36.7	--	6.9	5.9	--
	Cruise	--	--	5.9	(65.7)	--	8.1	6.7	--
	Idle	--	--	(7.5)	122.5	--	3.1	-1.1	--
Final (V-7/V-8)	**Takeoff**	(7.7)	30.0	7.0	46.2	6.8	(2.4)	--	--
	Cruise	8.9	17.1	--	83.2	27.1	13.0	--	--
	Idle	6.3	(8.3)	8.6	(56.4)	--	--	(-1.4)	(4.1)

Notes:
No parenthesis - correlation coefficient $0.8<r<1.0$
In parenthesis - correlation coefficient $0.6<r<0.8$
No value - correlation coefficient $r<0.6$

(a) percent change in value for a reduction from 14% to 13% fuel hydrogen.
(b) temperature differential is liner temperature minus inlet temperature.

combustor configuration. High smoke sensitivity at idle occurred in all configurations, but this effect is unimportant due to the low smoke levels at idle. NO_x emissions were consistently observed to increase with reduced fuel hydrogen. At high power, NO_x sensitivity averaged 7.5% with a maximum value of 13.4%. NO_x sensitivity was not affected by combustor modifications. Correlation coefficients for CO and HC were generally low, and no consistent effect on these emissions was observed.

Radiant heat flux and liner temperatures were both found to increase with decreasing fuel hydrogen, indicative of increased carbon particulate (smoke) formation. Sensitivity of average liner temperature was reduced to very low levels in the final configuration of each concept by the use of combustor modifications to reduce smoke formation (and radiation) and/or the incorporation of advanced cooling techniques. Maximum liner temperature sensitivity depended on the location of the maximum liner temperatures, as well as the average liner temperature. Combustor configurations having peak liner temperatures near the aft end of the liners tended to be less sensitive to fuel effects. Maximum liner temperatures in the final configuration of each concept were virtually unaffected by fuel hydrogen content.

The impact of increased liner temperature on combustor durability was evaluated with a simplified life estimation procedure describe in Reference 18. This procedure assumes that low cycle fatigue crack initiation is the liner failure mechanism and that the pseudoelastic stress is proportional to the thermal gradient within the liner which is, in turn, proportional to the differential between the peak liner temperature and the coolant temperature (or combustor inlet air temperature). With this procedure, the life reduction can be estimated based on the combustor service life (5000 cycles), liner material properties (HS188), and the change in maximum liner temperature differential at takeoff. Predicted life reduction sensitivity is shown as a function of liner temperature sensitivity in Figure 7-1. Here again, sensitivity refers to the percent change in life for a reduction from 14% to 13% fuel hydrogen.

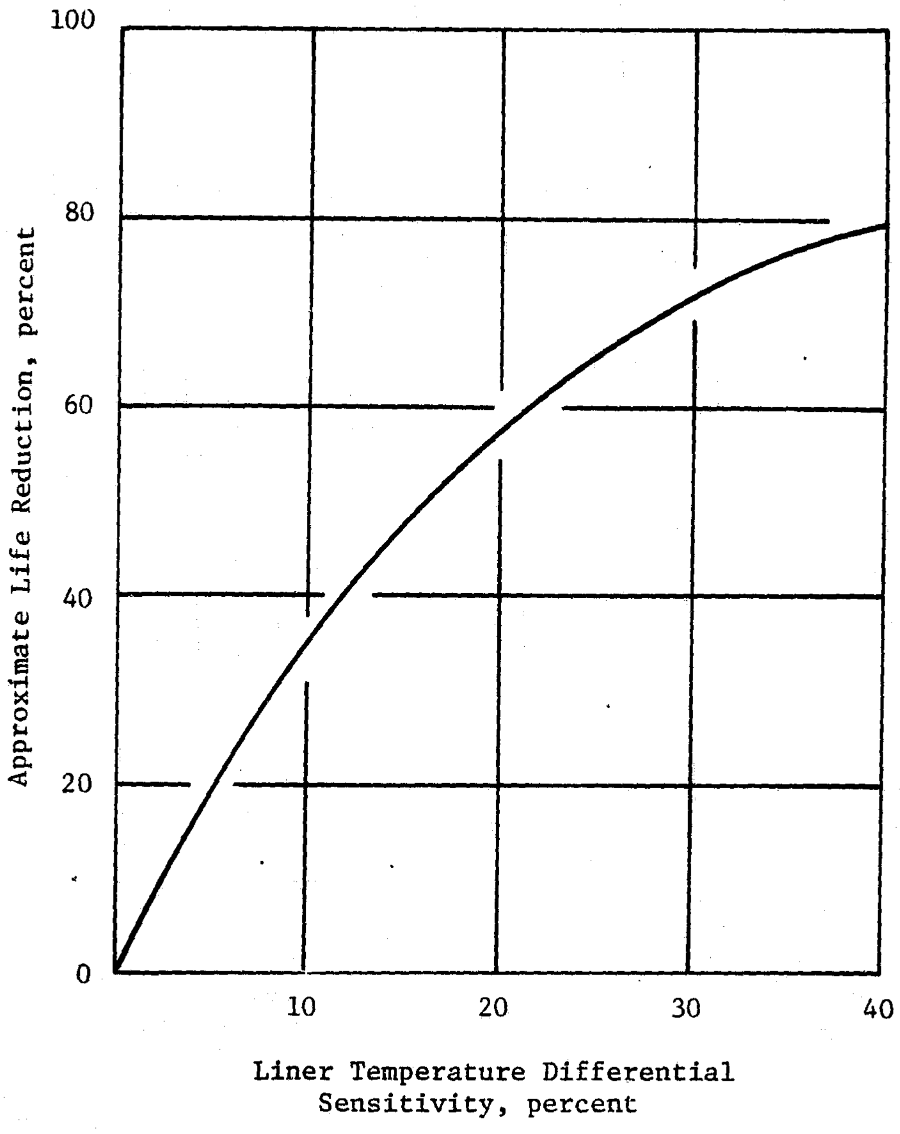

Figure 7-1. Relationship Between Liner Temperature Sensitivity and Combustor Life Reduction.

Combining the information from Table 7-2 and Figure 7-1, the predicted life reduction sensitivity of the baseline and final configurations of each combustor concept are as shown in Table 7-3. In the baseline single-annular and variable-geometry combustors, more than 30% life reduction was predicted. This was reduced to less than 5% in the final configuration of each concept. Thus, based on life considerations, any of the concepts could be operated satisfactorily on reduced hydrogen content fuels.

Although only limited ignition and blowout testing were conducted, the lower hydrogen fuels did tend to reduce combustor stability presumably due to poorer atomization. This effect was important in blowout tests of the single-annular combustor at altitude relight conditions, where combustor inlet pressures required for stable combustion were increased by over 20% with the reduced hydrogen content fuels. This change was sufficient to increase blowout pressure above the goal levels over much of the relight envelope.

In final analysis, the single-annular and variable-geometry combustors were selected for further evaluation and development during Phase II of the NASA/General Electric Broad-Specification Fuels Combustion Technology Program.

The single-annular combustor was selected because, based on the Phase I test results, the durability penalty due to the use of reduced hydrogen content fuels can be almost completely offset by relatively simple combustor modification. Other factors, such as reduced altitude relight capability, can also be offset with further development. Therefore, the use of the more complex advanced concepts is not warranted on the basis of fuel flexibility alone. The only program goal which is thought to be beyond the capability of the single-annular concept is the NO_x emissions limit. Since it was expected that the NO_x standard would be dropped by the EPA, consistent with internationl standards (Reference 19) the single-annular combustor was an obvious choice.

Table 7-3. Predicted Combustor Life Reduction.

Combustor Concept	Life Reduction Sensitivity, %	
	Baseline Configuration	Final Configuration
Single Annular	34	3
Double Annular	0	0
Variable Geometry	41	0*

*Data indicated life reduction of about 3%, but the correlation coefficient was less than 0.6 for takeoff data.

The measured emissions and performance characteristics of the variable-geometry combustor were generally inferior to those of the double-annular combustor; however, it was recognized that the variable-geometry concept was in a very early stage of development and that its full potential could not be realized during Phase I program. Considerable progress was made toward meeting the program goals, and no barrier problems were identified. It was judged that this concept had the potential to meet all of the program goals with further development. The variable-geometry combustor concept was selected over the double-annular concept because (1) it requires a smaller number of fuel nozzle/swirler assemblies, (2) the potential for fouling of unfueled main stage nozzles during operation at intermediate power is eliminated, and (3) the ability to continuously vary the vane opening provides additional flexibility for intermediate power operation. Additionally, the variable-geometry concept is believed to have high potential for use in short, high temperature rise, low pressure drop systems for next-generation engines. The simple variable swirler design used in this Phase I program proved to be quite reliable and easy to operate throughout the tests.

8.0 NOMENCLATURE

Symbol	Definition	Unit
CO	Carbon Monoxide	ppm
CO_2	Carbon Dioxide	%
ICO	CO Emission Index	g/kg
EIHC	HC Emission Index	g/kg
$EINO_x$	NO_x Emission Index	g/kg
EPAP	EPA Parameter	g/kN
FF	Reference Flow Function	-
f_m	Metered Fuel/Air Ratio	g/kg
f_s	Sample Fuel/Air Ratio	g/kg
G	Variable-Geometry Position	% open
h	Combustor Inlet Humidity	g/kg
HC	Unburned Hydrocarbons	ppm
NO_x	Oxides of Nitrogen	ppm
P	Total Pressure	MPa
P_s	Static Pressure	Mpa
P_{sa}	Sample Line Pressure	MPa
P_3	Combustor Inlet Total Pressure	MPa
P_{39}, P_4	Combustor Exit Total Pressure	MPa
P.F.	Pattern Factor	-
PROF	Profile Factor	-
Q_r	Radiant Heat Flux	kW/m^2
SN	Smoke Number	-
T	Total Temperature	K
T_f	Fuel Temperature	K
T_L	Average Liner Temperature	K
$T_{L,max}$	Peak Liner Temperature	K
T_{sa}	Sample Line Temperature	K
T_3	Combustor Inlet Total Temperature	K
T_{39}, T_4	Average Combustor Exit Total Temperature	K
V_r	Reference Velocity	m/s
W_b	Bleed Airflow	kg/s

Symbol	Definition	Unit
W_c	Combustor Airflow	kg/s
W_{fm}	Main Fuel Flow	g/s
W_{fp}	Primary Fuel Flow	g/s
W_{ft}	Total Fuel Flow	g/s
$\Delta P/P$	Combustion System Pressure Drop	%
ΔP_{fm}	Main Fuel Pressure Drop	MPa
ΔP_{fp}	Primary Fuel Pressure Drop	MPa
ϕ_m	Main Stage Primary Equivalence Ratio	-
ϕ_p	Pilot Stage Primary Equivalence Ratio	-
η_s	Sample Combustion Efficiency	%
η_{tc}	T/C Combustion Efficiency	%

9.0 REFERENCES

1. Friedman, R., "Aviation Turbine Fuel Properties and Their Trends," SAE Paper 810850, 1981.

2. Gleason, C.C. et al. "Evaluation of Fuel Character Effects on J79 Engine Combustion System," AFAPL TR-79-2015, 1979.

3. Gleason, C.C. et al. "Evaluation of Fuel Character Effects on F101 Engine Combustion System," AFAPL TR-79-2018, 1979.

4. Gleason, C.C. et al. "Evaluation of Fuel Character Effects on J79 Smokeless Combustor," AFWAL TR-80-2092, 1980.

5. Taylor, J.R., "Analytical Evaluation of Broad-Specification Fuels on High Bypass Turbofan Engine Combustors-Final Report," NASA CR-159641, 1979.

6. Kasper, J.M. et al. "Experimental Evaluation of Combustor Concepts for Burning Broad-Property Fuels," NASA CR-159855, 1980.

7. Fear, J.S., "NASA Broad Specification Fuels Combustion Technology Program - Status and Description," ASME Paper 80GT-65, 1980.

8. "Control of Air Pollution from Aircraft and Aircraft Engine-Proposed Amendments to Standards," Federal Register, Vol. 43, No. 58, pp. 12615-12634, March 24, 1978.

9. Longwell, J.P., Ed., "Jet Aircraft Hydrocarbon Fuels Technology," NASA CP 2033, 1978.

10. Gleason, C.C. and Niedzwiecki, R.W., "Results of the NASA/General Electric Experimental Clean Combustor Program," AIAA Paper No. 76-763, 1976.

11. Bahr, D.W., Burrus, D.L., and Sabla, P.E., "QCSEE Double-Annular Clean Combustor Technology Development Report," NASA CR-159483, May 1979.

12. Burrus, D.L. et al. "Energy Efficient Engine-Combustion System Component Technology Development Report," NASA Contractor Draft Report (GE Report R82AEB401), November 1982.

13. Seng, G.T., "Characterization of an Experimental Referee Broadened-Specification (ERBS) Aviation Turbine Fuel and ERBS Fuel Blends," NASA TM 82883, 1982.

14. Jasuja, A.K., "Atomization of Crude and Residual Oils," ASME Paper 78-GT-83, April 1978.

15. Gleason, C.C. and Bahr, D.W., "Experimental Clean Combustor Program - Phase III Final Report," NASA CR-135384, 1979.

16. Lyon, T.F., Dodds, W.J., and Bahr, D.W., "Determination of the Effects of Ambient Conditions on CFM56 Aircraft Engine Emissions," EPA-460/ 3-79/011, December 1979.

17. Schaffernocker, W.M. and Stanforth, C.M., "Smoke Measurement Techniques," SAE Paper 680346, April 1968.

18. Foltz, H.L. and Kenworthy, M.J., "A Procedure for Evaluating Fuel Composition Effects on Combustor Life," ASME Paper 82-GT-296, 1982.

19. International Civil Aviation Organization, "International Standards and Recommended Practices-Environmental Protection," Annex 16 to the Convention on International Civil Aviation, Vol. II, Aircraft Engine Emissions, 1981.

APPENDIX

SUMMARY OF TEST RESULTS

This appendix contains summaries of test conditions, combustor performance, and exhaust emissions data measured on each test conducted during this program. These tables are ordered according to the combustor concept:

Concept	Tables
Single Annular	A-1 to A-10
Double Annular	A-11 to A-16
Variable Geometry	A-17 to A-25

Except for Table A-9, each table has three sheets. Sheet 1 summarizes combustor inlet conditions and performance; Sheet 2 presents emissions data; and Sheet 3 presents detailed liner temperature data. Table A-9 presents altitude relight data for single-annular Configuration S-9. Data for each concept are ordered by increasing inlet temperatures.

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TABLE A - 1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-1/S-2 RUN NUMBER 3 DATE 4/23/81 SHEET 1

ID		COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/ AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
29	IDL	431	.304	2.14	2.16	0.49	--	Jet A	35.3	35.3	294	0.796	--	16.4	15.6	0.97	4.12	509	540		877	1091	1.26	.48	
30		458	.383	2.14	2.81	0.62			42.3	42.3	294	1.127	--	15.1	17.0	1.03	4.80	561	594		922	1126	1.23	.44	
34	APP	608	1.114	2.14	7.09	1.65			93.6	58.3	293	2.011	0.022	13.2	19.7	1.03	4.55	684	754		1042	1257	1.22	.50	89
35	CRU	689	.946	2.14	5.55	1.27			100.4	59.4	294	2.007	0.027	18.1	20.5	1.02	4.40	790	866		1219	1481	1.22	.49	83
36	CLT	771	1.465	2.14	7.96	1.81			166.7	33.1	292	0.832	0.337	20.9	21.3	0.99	3.93	951	1015		1385	1705	1.24	.52	86
37	T/O	803	1.674	2.14	8.97	2.03			203.7	32.4	293	0.854	0.552	22.7	21.8	1.00	4.21	1014	1096		1458	1811	1.25	.54	86
38		803	1.671	2.14	8.84	2.02			202.4	32.2	293	0.846	0.545	22.9	21.5	0.98	3.82	1015	1101		1458	1813	1.24	.54	85
39		802	1.911	2.03	10.40	2.36			229.6	36.4	293	1.073	0.692	22.1	22.1	1.02	4.39	1011	1101		1464	1810	1.25	.52	89
42	CRU	689	.937	2.14	5.75	1.11		ERBS 11.8	100.3	58.3	293	1.769	0.035	18.0	20.4	1.03	4.68	851	904		1209	1455	1.24	.47	
41	CLI	771	1.465	2.14	8.17	1.71			166.6	32.8	292	0.749	0.323	20.4	21.5	1.02	4.38	1008	1099		1374	1666	1.25	.48	
40	T/O	804	1.677	1.86	8.92	2.13			200.6	31.5	293	0.778	0.512	22.5	21.9	0.99	4.34	1053	1161		1445	1796	1.25	.55	
48	IDL	426	.303	2.14	2.15	0.40		ERBS 12.8	35.5	35.5	292	0.638	--	16.5	14.9	0.96	4.35	540	573		876	1018	1.20	.31	
47	CRU	679	.937	2.14	5.43	1.15			100.2	58.8	293	1.710	0.037	18.4	19.7	0.99	4.71	830	884		1224	1465	1.25	.44	85

TABLE A - 1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-1/S-2 RUN NUMBER 3 DATE 4/23/81 SHEET 2

ID		COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	$\bar{T}_L$ - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
46	CLI	771	1.467	2.14	8.32	1.70	--	ERBS 12.8	167.6	81.0	293	3.454	0.132	20.1	21.8	1.04	4.64	963	1026	--	1358	1623	1.26	0.45	86
45		771	1.464	2.14	8.30	1.70			168.0	33.5	293	0.787	0.337	20.2	21.8	1.04	4.62	999	1066		1369	1665	1.26	0.49	88
44	T/O	799	1.680	2.14	9.04	1.96			202.1	75.9	293	3.323	0.284	22.3	21.7	1.00	4.25	1021	1091		1450	1747	1.25	0.46	88
43		803	1.680	2.14	9.17	1.90			203.7	32.3	292	0.803	0.535	22.2	21.9	1.02	4.44	1048	1134		1453	1769	1.25	0.49	88

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-1/S-2 **RUN NUMBER** 3 **DATE** 4/23/81 **SHEET**

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
29		625	3.14	66.7	32	8.6	--	379		39.2	2.39	3.26	15.68	98.88	2.96		0.96	4.38	26.1	--		1.00	0.57		Blowout W_f=9.58 g/s (f_m=4.44 g/kg)	1
30		434	3.47	13.9	46	--	.221	406		24.8	0.45	4.32	17.21	99.38	--		1.14	4.50	26.3	--		1.00	0.64			1
34		81	2.81	3.7	111	--	1.034	392		5.8	0.15	12.93	13.76	99.85	12.15		1.04	4.26	27.1	156		0.62	0.49			1
35		222	3.57	2.4	146	7.1	.820	410		12.4	0.08	13.45	17.59	99.70	12.33		0.97	4.30	27.6	164		0.59	0.67			1
36		287	4.69	4.1	256	23.3	1.393	435		12.3	0.10	17.89	23.24	99.70	20.01		1.11	3.98	23.9	152		0.20	0.78			1
37		354	5.00	4.5	336	33.0	.600	444		14.1	0.10	22.01	24.86	99.66	25.11		1.10	4.22	23.1	152		0.16	0.84			1
38		336	5.07	6.4	327	--	.290	443		13.2	0.14	21.15	25.19	99.68	23.81		1.10	4.21	24.0	152		0.16	0.84		Element C1--Low Flow E1--No Flow	3
39		282	4.63	3.7	345	48.8	.283	394		12.2	0.09	24.40	22.95	99.71	26.86		1.04	4.36	23.2	153		0.16	0.82			1
42		234	3.88	2.1	183	15.1	.241	427		12.3	0.06	15.76	18.70	99.70	14.35		1.04	4.43	28.9	148		0.58	0.67			1
41		281	4.86	3.0	306	29.8	.283	445		11.8	0.07	21.13	23.49	99.71	23.94		1.15	4.22	25.0	155		0.20	0.76			1
40		295	5.17	3.7	380	33.0	.290	454		11.6	0.08	24.64	25.04	99.71	27.89		1.11	4.36	21.3	156		0.16	0.83			1
48		841	3.19	70.3	370	23.9	.228	389		52.0	2.49	3.76	15.90	98.56	3.35		0.96	4.69	29.3	--		1.00	0.61		Blowout W_f=8.92 g/s (f_m=4.15 g/kg)	1
47		270	4.03	1.3	1559	9.4	.313	424		13.5	0.04	12.80	19.72	99.68	11.89		1.07	4.77	29.7	141		0.59	0.68			1

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-1/S-2 **RUN NUMBER** 3 **DATE** 4/23/81 **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS							STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}		W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
46		254	4.42	2.4	252	18.0	.820	436		11.57	0.06	18.86	21.66	99.72	21.60		1.08	4.32	28.7	157			.48	0.75		Configuration S-2	1
45		247	4.48	2.8	269	24.9	.283	446		11.11	0.07	19.83	21.96	99.73	22.69		1.09	4.31	24.9	152			.20	0.75			1
44		304	4.76	3.0	325	31.5	.296	452		12.86	0.07	22.55	23.37	99.70	25.94		1.05	4.24	27.4	156			.38	0.83		Configuration S-2	1
43		299	4.81	2.5	340	41.2	.296	453		12.52	0.06	23.38	23.62	99.70	26.73		1.06	4.28	23.7	155			.16	0.82			1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-1/S-2 RUN NUMBER 3 DATE 4/23/81 SHEET 1

ID	COMBUSTOR METAL TEMPERATURES, K																				
	OUTER LINER						INNER LINER							DOME							
PANEL	1	1	3	3	5	5	1	1	3	3	5	5	AVG	OUTER			INNER			AVG
ANGLE	0	6	0	6	0	6	0	6	0	6	0	6	LINER	CUP 4	CUP 5	DOME	CUP 4	CUP 5	DOME	DOME
29	489	523	501	528	540	560	511	523	–	508	457	457	509	646	428	499	540	574	549	539
30	539	580	561	593	575	607	562	584		594	485	489	561	678	471	588	608	630	600	596
34	661	676	688	703	748	754	661	669		708	629	630	684	1345	579	669	683	716	675	778
35	774	785	800	810	860	866	774	775		816	718	720	790	1060	649	776	795	803	779	810
36	948	953	964	959	1014	1015	939	970		1015	856	827	951	--	664	879	888	893	889	843
37	998	1010	1016	1021	1073	1096	1001	1045		1096	918	876	1014	--	664	916	928	926	936	874
3[illegible]	999	1010	1018	1020	1072	1092	1003	1052		1101	918	878	1015	--	663	918	928	928	934	874
39	993	1005	1009	1015	1069	1098	990	1045		1101	917	878	1011	--	651	914	--	918	929	853
42	849	884	849	852	880	892	853	894		904	756	742	851	892	614	821	830	808	823	798
41	1020	1036	1020	1000	1043	1054	999	1064		1099	900	853	1008	915	651	914	909	886	921	866
40	1051	1074	1055	1046	1092	1115	1034	1115		1161	946	895	1053	1103	663	944	--	929	960	920
48	530	559	535	561	555	573	561	552		556	479	474	540	--	478	544	562	533	584	540
47	823	858	824	835	863	884	832	860		870	747	730	830	--	599	805	821	763	802	758
46	954	1006	967	971	1004	997	958	997		1026	869	836	963	860	645	904	897	847	899	842
45	1000	1051	991	1010	1019	1053	980	1031		1066	884	846	994	816	638	895	914	843	906	835

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-1/S-2 RUN NUMBER 3 DATE 4/23/81 SHEET 2

ID	COMBUSTOR METAL TEMPERATURES, K																			
	OUTER LINER						INNER LINER							DOME						
PANEL	1	1	3	3	5	5	1	1	3	3	5	5	AVG	OUTER			INNER			AVG
ANGLE	0	6	0	6	0	6	0	6	0	6	0	6	LINER	CUP 4	CUP 5	DOME	CUP 4	CUP 5	DOME	DOME
44	1007	1064	1028	1029	1067	1091	1010	1050	--	1090	920	874	1021	856	656	936	922	888	940	866
43	1038	1099	1048	1069	1087	1119	1021	1090		1134	938	889	1048	746	655	934	939	894	953	854

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TABLE A - 2

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S -3 RUN NUMBER 4 DATE 5/1/81 SHEET 1

READING	ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
50	IDL	439	0.303	2.59	2.26	.49		Jet A	35.3	35.3	291	0.922	--	15.6	16.4	1.03	4.82	524	566		922	1091	1.35	.35	
51	APP	611	1.113	2.26	7.08	1.65		↓	93.1	58.1	293	2.501	.003	13.2	19.8	1.03	4.31	706	770		1043	1256	1.27	.50	
52	CRU	685	0.945	2.36	5.55	1.25		↓	100.0	58.4	293	2.546	.017	18.0	20.4	1.01	4.32	813	879		1235	1466	1.25	.42	
54	CLI	770	1.466	3.43	8.26	1.84		↓	166.0	32.7	291	1.061	.315	20.1	21.9	1.03	4.32	953	1033		1235	1704	1.27	.56	
55	T/O	803	1.684	3.79	8.88	2.04		↓	202.8	31.8	291	1.111	.516	22.8	21.5	0.98	4.05	1020	1115		1469	1827	1.26	.54	
56		802	1.910	5.57	9.77	2.31		↓	229.0	37.2	290	1.477	.646	23.4	21.0	0.95	3.72	1032	1135		1505	1866	1.25	.51	
61	IDL	432	0.303	1.94	1.95	.51		ERBS 12.8	202.4	32.9	289	0.917	--	18.2	14.4	0.88	3.54	583	633		933	1081	1.22	.29	
60	APP	623	1.107	3.14	7.32	1.46		↓	168.3	34.1	290	2.481	.012	12.9	20.5	1.08	4.97	733	803		1038	1209	1.26	.41	
59	CRU	688	0.938	3.43	5.59	1.09		↓	100.7	58.9	290	2.495	.020	18.0	20.3	1.03	4.44	910	941		1239	1427	1.23	.34	
58	CLI	771	1.465	3.57	8.47	1.65		↓	94.1	58.8	289	1.096	.315	19.9	22.1	1.06	4.76	980	1078		1347	1639	1.26	.51	
57	T/O	805	1.682	5.57	8.68	2.07		↓	35.5	35.5	292	1.138	.502	2303	21.3	0.96	4.30	1045	1160		1461	1783	1.24	.49	

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-3 **RUN NUMBER** 4 **DATE** 5/1/81 **SHEET** 1

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLE MODE
50		538	3.23	39.8	--	2.0	.213	370		32.9	1.39	3.62	16.06	99.11	3.39		1.03	4.56	24.2	--		1.00	.58			1
51		95	3.05	3.2	--	6.2	.434	374		6.2	0.12	11.36	14.94	99.84	10.56		1.13	4.03	24.2	428		.62	.49			1
52		258	4.13	2.0	--	12.9	.421	381		12.5	0.05	12.47	20.42	99.70	11.60		1.13	4.21	24.1	212		.58	.67			1
54		203	4.76	0.9	--	19.5	.572	402		8.5	0.02	19.11	23.56	99.80	22.69		1.17	4.08	20.9	157		.20	.75			1
55		260	5.18	0.7	357	32.0	.365	383		10.0	0.02	22.64	25.72	99.76	26.19		1.13	4.20	19.9	157		.16	.85			1
56		266	5.24	2.7	377	40.3	.421	424		10.1	0.06	23.59	26.04	99.76	26.27		1.11	4.10	20.2	157		.16	.87			1
61		1101	3.81	100.4	48	42.3	.207	381		56.7	2.96	4.09	19.13	98.41	3.43		1.05	4.60	24.4	--		.16	.68		Blowout W_f=8.55 g/s (f_m=4.39 g/kg)	1
60		89	2.89	3.0	115	13.9	.296	357		6.2	0.12	13.25	14.02	99.84	12.23		1.09	4.23	24.6	211		.20	.48			1
59		213	3.99	2.0	168	25.9	.255	402		10.8	0.06	13.97	19.49	99.74	13.06		1.08	4.22	24.6	196		.58	.67			1
58		191	4.50	1.8	297	21.8	.276	400		8.6	0.05	21.86	22.02	99.79	25.96		1.11	4.25	21.5	158		.62	.74			1
57		241	5.17	2.7	386	45.5	.317	418		9.4	0.06	24.75	25.37	99.77	29.06		1.09	4.62	20.3	158		1.00	.86			1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-3 RUN NUMBER 4 DATE 5/1/81 SHEET 1

ID COMBUSTOR METAL TEMPERATURES, K

	OUTER LINER						INNER LINER							DOME						
PANEL	1	1	3	3	5	5	1	1	3	3	5	5	AVG	OUTER			INNER			AVG
ANGLE	0	6	0	6	0	6	0	6	0	6	0	6	LINER	CUP 4	CUP 5	DOME	CUP 4	CUP 5	DOME	DOME
50	509	536	531	547	--	566	461	539	--	559	472	--	524	--	--	541	--	516	543	533
51	680	714	696	730	--	769	623	715		766	658		706	--	--	688	--	644	689	674
52	795	825	812	833	--	879	705	832		878	759		813	--	--	789	--	745	790	775
54	953	984	965	971	--	1028	798	971		1033	870		953	--	--	884	--	831	884	866
55	1011	1056	1028	1052	--	1110	833	1043		1115	929		1020	--	--	925	--	861	934	907
56	1013	1069	1039	1069	--	1134	834	1053		1135	941		1032	--	--	929	--	851	938	906
61	576	609	578	616	--	610	480	627		633	514		583	--	--	554	--	549	591	564
60	715	740	730	751	--	787	638	755		803	678		733	--	--	703	--	641	709	684
59	848	878	854	871	--	902	719	894		941	785		854	--	--	811	--	743	822	792
58	994	1029	987	1000	--	1038	803	1012		1078	883		980	--	--		--			
57	1043	[illegible]	1050	1076	--	1118	839	1078		1160	946		1045	--	--	944	--	854	953	917

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TABLE A - 3

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 4 RUN NUMBER 5 DATE 5/4/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
62		431	.303	3.57	2.18	0.47			Jet A	35.3	35.3	290	0.922	--		16.2	15.6	0.98		4.35	501	549	--	855	999	1.26	.34	
63		433	.305	3.57	2.22	0.49				35.4	35.4	290	0.920	--		16.0	15.9	1.00		4.53	502	549		855	994	1.25	.33	
64		616	1.108	2.14	7.45	1.59				94.6	59.2	290	2.559	--		12.7	20.8	1.10		4.51	694	751		1009	1182	1.25	.44	
65		686	.940	1.86	5.35	1.29				102.0	59.9	290	2.650	0.012		19.1	20.1	0.98		4.09	821	886		1216	1450	1.23	.44	
66		764	1.460	2.14	7.97	1.89				168.5	33.7	290	1.076	0.312		21.1	21.3	0.99		4.07	943	1032		1357	1668	1.29	.52	
67		802	1.678	2.59	8.96	2.03				202.8	32.6	290	1.105	0.499		22.6	21.7	0.99		4.01	1008	1116		1448	1804	1.29	.55	
68		805	1.673	2.36	8.96	2.04				173.3	28.1	290	0.816	0.362		19.3	21.9	1.00		4.00	974	1083		1361	1685	1.31	.58	
69		805	1.912	2.14	10.26	2.32				230.4	36.7	290	1.418	0.649		22.4	21.9	1.00		4.09	1012	1119		1451	1806	1.29	.55	
75		433	.306	4.43	2.13	0.48			ERBS 12.8	34.9	34.9	296	0.828	--		16.4	15.3	0.95		4.35	529	565		854	994	1.27	.33	
74		614	1.105	2.36	7.01	1.67				93.8	58.9	296	2.414	--		13.4	19.9	1.04		4.60	717	766		1011	1209	1.25	.50	
72		683	.940	2.46	5.53	1.78				101.2	33.4	293	1.009	0.038		21.0	21.4	1.01		4.58	841	912		1183	1424	1.26	.48	
71		771	1.459	2.14	7.99	1.28				167.8	59.4	294	2.477	0.318		18.3	20.3	1.00		4.29	980	1077		1353	1670	1.29	.54	
73		804	.974	2.46	5.21	1.22				118.1	19.7	294	0.371	0.166		22.7	21.9	1.00		4.43	1011	1095		1369	1682	1.29	.55	
70		805	1.678	2.14	8.99	2.02				203.3	32.4	292	1.040	0.498		22.6	218	1.00		4.22	1036	1154		1440	1763	1.28	.51	

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TABLE A - 3

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 4 RUN NUMBER 5 DATE 5/4/81 SHEET 2

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
80		436	.307	4.43	2.20	0.75	--		ERBS 12.3	33.4	33.4	298	0.758	--		15.2	17.3	0.98		5.44	511	559		813	932	1.21	.32	
79		685	.940	4.29	5.58	1.26	--			97.5	55.9	299	2.234	0.018		17.5	20.6	1.02		4.58	840	915		1164	1409	1.25	.51	
78		803	1.675	4.79	8.80	1.66	--			200.8	0	300	--	0.731		22.8	21.5	0.98		3.93	1040	1159		1420	1744	1.28	.53	
77		802	1.680	4.43	8.89	2.06	--			198.9	30.7	301	0.949	0.474		22.4	21.6	0.99		4.02	1036	1153		1421	1754	1.29	.54	

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-4 **RUN NUMBER** 5 **DATE** 5/4/81 **SHEET** 2

ID	MEASURED EMISSIONS							EMISSIONS CALCULATIONS						RATIOS						STOICHIOMETRY		COMMENTS	
READING	CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K	EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg	f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
62	759	3.18	91.7	34	13.4	.200	385	46.7	3.23	3.43	15.97	98.63	3.22	.99	4.50	24.2	--		1.00	.60			1
63	771	3.20	106.0	34	—	.200	358	47.1	3.71	3.43	16.10	98.58	3.23	1.01	4.57	24.3	--		1.00	.59			1
64	66	2.91	6.4	102	9.9	.255	378	4.6	0.25	11.60	14.22	99.87	11.08	1.12	3.74	24.4	--		0.63	.47			1
65	186	4.17	3.3	187	24.0	.234	378	8.9	0.09	14.72	20.59	99.78	13.27	1.08	4.25	24.3	255		0.59	.71			1
66	198	4.77	3.6	301	32.6	.290	380	8.3	0.09	20.73	23.59	99.80	24.21	1.12	4.13	21.4	159		0.20	.78			1
67	246	5.16	3.7	391	45.4	.310	386	9.5	0.08	24.86	25.60	99.77	28.53	1.13	4.05	20.4	159		0.16	.84			1
68	98	4.22	2.9	352	22.2	.303	384	4.7	0.08	27.41	20.79	99.88	31.13	1.08	4.00	20.5	159		0.16	.72			1
69	186	4.89	2.8	379	33.8	.310	386	7.6	0.07	25.50	24.20	99.82	27.32	1.08	4.07	20.3	158		0.16	.83			1
75	686	3.17	114.2	36	17.4	.200	372	42.7	4.08	3.70	15.76	98.64	3.41	.96	4.78	25.3	--		1.00	.61			1
74	67	2.89	4.1	110	9.9	.276	385	4.7	0.16	12.58	14.02	99.88	11.71	1.05	4.30	25.0	--		0.63	.50			1
72	140	3.15	2.3	169	18.7	.269	381	7.4	0.07	14.54	18.74	99.82	13.70	1.02	4.48	24.9	203		0.59	.68			1
71	173	4.68	2.8	314	32.3	.317	388	7.5	0.07	22.22	22.92	99.82	24.94	1.09	4.29	21.9	160		0.20	.78			1
73	318	4.94	2.4	313	28.9	.262	380	12.6	0.06	20.95	24.29	99.70	29.85	1.07	4.46	21.4	159		0.17	.84			1
70	200	5.08	2.9	394	42.9	.310	388	8.0	0.07	25.69	24.93	99.81	29.00	1.10	4.22	21.0	159		0.16	.84			1

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-4 | RUN NUMBER 5 | DATE 5/4/81 | SHEET 2 Cont'd

ID	MEASURED EMISSIONS							EMISSIONS CALCULATIONS					
READING	CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K	EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg
80	731	2.76	225	--	9.2	.200	355	52.3	9.20	4.40	13.69	97.97	--
79	111	3.70	0.6	168	13.4	.255	383	6.1	0.02	15.18	17.84	99.85	14.85
78	196	4.99	2.0	373	30.4	.296	394	8.0	0.05	24.96	24.22	99.81	29.34
77	179	4.91	0.9	383	32.9	.310	393	7.4	0.02	26.08	23.85	99.82	30.79
77	194	4.94	0.9	382	--	.310	393	8.0	0.02	25.87	23.96	99.81	30.54

ID	RATIOS						STOICHIOMETRY		COMMENTS	
READING	f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
80	--	--	--	--		1.00	--		Blowout W_f=10.1 g/s (f_m=4.58 g/kg)	1
79	1.02	4.39	24.7	206		0.57	.65			1
78	1.06	4.09	--	155		0	.85			1
77	1.06	4.14	20.8	161		0.15	.83			1
77	1.07	4.14	20.8	161		0.15	.83			2

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-4 RUN NUMBER 5 DATE 5/4/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																			
	OUTER LINER						INNER LINER							DOME						
PANEL	1	1	3	3	5	5	1	1	3	3	5	5	AVG	OUTER			INNER			AVG
ANGLE	0	6	0	6	0	6	0	6	0	6	0	6	LINER	CUP 4	CUP 5	DOME	CUP 4	CUP 5	DOME	DOME
62	484	504	506	526		549	447	510	--	526	464	--	501	--	--	493	552	499	502	511
63	486	502	509	525		549	448	509		523	464		502			494	556	502	506	514
64	675	690	707	703		751	627	710		733	650		694			674	775	627	691	692
65	814	828	825	825		820	716	863		886	759		821			780	855	728	793	781
66	942	970	943	953		1015	794	974		1032	863		943			880	922	795	880	869
67	999	1039	1000	1026		1090	836	1045		1117	923		1008			928	960	843	931	860
68	971	1001	969	984		1040	830	999		1083	891		974			912	931	833	903	895
69	999	1048	1005	1036		1099	835	1043		1119	923		1012			927	954	835	928	911
75	514	540	535	555		565	461	551		560	480		529			523	570	518	536	537
74	706	727	713	724		766	633	755		766	661		717			684	775	616	704	695
72	841	860	845	846		884	719	893		912	769		841			791	870	718	808	796
71	989	1026	982	992		1036	808	1018		1077	889		980			909	939	796	904	887
73	1031	1053	1015	1025		1058	850	1056		1095	923		1011			955	994	852	946	937
70	1034	1084	1028	1058		1104	844	1080		1154	941		1036			951	971	832	948	925

TABLE A - 4

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 5 RUN NUMBER 6 DATE 5/10/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
91		438	.289	4.29	2.30	0.48			ERBS 12.8	35.2	35.2	294	.665	--		15.3	17.4	10.51		4.28	485	512		855	1039	1.44	0.44	
90		612	1.098	4.29	7.07	1.60				94.1	54.8	295	1.661	--		13.3	20.0	10.08		5.19	690	759		1085	1197	1.24	0.24	
89		682	.932	4.29	5.64	1.27				99.7	55.1	295	1.678	.015		17.7	20.9	9.98		5.09	801	907		1277	1419	1.24	0.24	
88		770	1.464	4.29	7.93	1.84				166.8	42.1	296	.980	.693		21.0	21.2	9.49		4.51	914	1019		1465	1551	1.13	0.13	
85		775	2.435	4.29	13.00	3.05				276.5	53.7	296	1.449	.845		21.3	21.1	9.39		4.23	928	1041		1493	1626	1.12	0.19	
87		801	2.714	4.29	13.91	3.66				335.6	52.0	296	1.498	1.386		24.1	21.4	9.18		4.09	969	1086		1548	1713	1.22	0.22	
86*		798	2.799	4.29	13.25	3.86				3348	52.0	298	1.499	1.382		25.3	20.1	8.46		4.00	964	1076		1604	1729	1.15	0.15	
84		797	1.908	4.29	10.58	2.30				229.4	36.4	295	.890	.634		21.7	22.2	9.89		4.99	946	1060		1490	1651	1.12	0.23	
83		803	1.679	4.29	9.67	2.04				203.6	32.9	294	.734	.497		21.1	23.2	10.33		4.80	955	1069		1488	1663	1.14	0.26	
82		803	.963	9.57	5.14	1.18				118.1	19.7	293	.292	.164		23.0	21.8	9.55		4.92	939	1028		1436	1619	1.14	0.29	

*RDG 86 switch to verify full flow. RDG 86-90 W_{fp} based on manifold ΔP.

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-4 RUN NUMBER 5 DATE 5/4/81 SHEET 3 CONT'D.

ID	COMBUSTOR METAL TEMPERATURES, K																			
	OUTER LINER						INNER LINER							DOME						
PANEL	1	1	3	3	5	5	1	1	3	3	5	5	AVG	OUTER			INNER			AVG
ANGLE	0	6	0	6	0	6	0	6	0	6	0	6	LINER	CUP 4	CUP 5	DOME	CUP 4	CUP 5	DOME	DOME
80	490	519	506	543	--	559	456	514	--	534	476		511	--	--	508	574	505	520	527
79	839	863	837	841		877	720	902		915	766		840			791	871	723	814	800
78	1043	1091	1031	1060		1103	843	1088		1159	943		1040			959	966	847	947	930
77	1038	1088	1027	1054		1100	840	1085		1153	938		1036			955	966	836	946	926

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-5 RUN NUMBER 6 DATE 5/12/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
91		1016	2.92	357	57.4	5	.214	365		67.3	13.54	6.3	14.81	97.25	6.5		0.96	3.58	28.4	--		1.00			Drifting Through T_3	
90		67	3.18	13	113	5	--	366		4.2	0.47	11.8	15.43	99.86	11.5		1.16	4.73	28*	--		.58				
89		84	3.94	13	172	5	.241	367		4.3	0.37	14.5	19.20	99.87	14.7		1.08	4.72	28*	--		.55				
88		83	4.55	13	344	5	.269	360		3.7	0.34	25.1	22.23	99.88	29.3		1.06	4.62	28*	--		.25				
85		67	4.72	20	--	16	.407	391		2.9	0.49	30.7	23.05	99.89	28.5		1.08	4.43	29.4	--		.19				
87		--	--	--	--	6	--	--		--	--	--	--	--	--		--	4.79	28*	164.8		.16				
86		86	5.09	16	--	15	.448	392		3.4	0.36	35.2	24.89	99.89	32.2		0.98	5.17	28*	164.6		.16				
84		64	4.61	28	440	15	.317	368		2.8	0.69	31.7	22.52	99.87	37.5		1.04	4.71	25.4	159.9		.16				
83		73	4.60	24	403	30	.283	361		3.2	0.60	29.2	22.44	99.87	36.6		1.06	4.17	25.3	159.5		.16				
82		91	4.23	--	--	6	--	345		4.3	--	--	20.65	--	--		0.90	4.97	24.0	160.1		.17				

*Assumed

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-5 RUN NUMBER 6 DATE 5/12/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																			
	OUTER LINER						INNER LINER							DOME						
														OUTER			INNER			
PANEL	1	1	3	3	5	5	1	1	3	3	5	5	AVG							AVG
ANGLE	0	6	0	6	0	6	0	6	0	6	0	6	LINER	CUP 4	CUP 5	DOME	CUP 4	CUP 5	DOME	DOME
91	493	503	494	504	469	--	451	512	--	--	471	465	485	--	--	468	527	--	471	489
90	700	739	695	712	671	--	629	759	--	--	659	646	690	--	--	685	725	--	691	701
89	813	860	806	824	783	--	717	907	--	--	760	738	801	--	--	804	851	--	797	818
88	923	1005	920	953	899	--	806	1019	--	--	869	835	914	--	--	930	944	--	913	929
85	931	1038	939	976	900	--	807	1040	--	--	880	841	928	--	--	938	918	--	924	926
87	970	1074	989	1022	978	--	833	1086	--	--	921	874	969	--	--	964	953	--	952	956
86	964	1070	984	1018	954	--	829	1076	--	--	916	870	964	--	--	964	943	--	950	953
84	946	1052	945	993	936	--	830	1060	--	--	891	861	946	--	--	955	950	--	952	953
83	958	1064	956	1001	943	--	838	1069	--	--	845	870	955	--	--	981	969	--	965	971
82	947	1017	944	982	930	--	841	1028	--	--	838	868	939	--	--	978	993	--	950	973

TABLE A - 5

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 6 RUN NUMBER 7 DATE 5/15/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEO. POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
99		616	1.107		7.10	1.61	--		Jet A	93.9	59.0	294	2.599	.010		13.2	20.0	10.00		4.99	650	703	--	1108	1193	1.17	.17	
98		983	.939		5.45	1.25	--			100.3	59.5	293	2.641	.024		18.4	20.7	9.86		4.85	736	786	--	1349	1454	1.16	.16	
96		774	2.445		13.28	3.16	--			274.4	62.9	294	2.881	.888		20.7	21.5	9.55		4.69	897	991	--	1531	1629	1.13	.13	
97		803	2.800		15.03	3.48	--			335.3	64.1	294	2.921	1.452		22.3	22.0	9.61		4.66	939	1037	--	1602	1709	1.13	.13	
95		802	1.902		10.31	2.29	--			229.9	43.5	293	1.413	.673		22.2	22.0	9.70		4.63	945	1050	--	1604	1721	1.14	.14	
94		804	1.681		9.29	2.09	--			203.2	38.9	293	1.133	.533		21.9	22.5	9.89		4.79	949	1050	--	1594	1691	1.12	.12	
93		802	1.385		7.35	1.67	--			167.2	31.9	293	.778	.365		22.7	21.6	9.49		4.51	953	1052	--	1617	1848	1.16	.28	

ORIGINAL PAGE IS OF POOR QUALITY

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-6 RUN NUMBER 7 DATE 5/15/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
99		41	2.96	7.4	102	1.9	.248	374		2.8	0.29	11.34	14.49	99.91	11.25		1.10	4.56	24.1	--		.63				
98		77	3.95	8.1	154	2.7	.221	369		3.9	0.24	12.84	19.40	99.89	13.40		1.05	4.91	24.1	172		.41				
96		51	4.46	9.5	363	6.7	.414	396		2.3	0.24	26.79	21.97	99.92	26.25		1.06	4.75	24.4	148		.23				
97		67	4.85	9.4	467	6.0	.448	400		2.8	0.22	31.77	23.93	99.92	32.05		1.07	4.66	24.7	148		.19				
95		94	4.81	10.3	424	7.4	.345	377		3.9	0.25	28.97	23.78	99.89	34.33		1.07	4.54	24.1	150		.19				
94		111	4.85	14.6	432	4.2	.296	371		4.6	0.34	29.34	23.96	99.86	37.07		1.09	4.51	24.0	148		.19				
93		161	4.89	20.1	392	5.6	.276	366		6.6	0.47	26.40	24.18	99.80	35.08		1.07	4.62	23.8	148		.19				

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-6 RUN NUMBER 7 DATE 5/15/81 SHEET 3

ID																											
										COMBUSTOR METAL TEMPERATURES, K																	
				OUTER LINER										INNER LINER								DOME					
PANEL	1	1	3	3	5	5					1	1	3	3	5	5				LINER	OUTER			INNER			DOME
ANGLE	0	6	0	6	0	6					0	6	0	6	0	6				AVG							AVG
99	–	690	679	703	527	–					623	686	647	–	650	643				650	–	–	691	699	–	683	690
98	–	786	770	753	595	–					697	785	731	–	738	725				736	–	–	787	794	–	773	785
96	–	991	923	956	877	–					793	990	852	–	863	829				897	–	–	909	869	–	905	894
97	–	1037	961	1004	934	–		984	1	181	824	1036	888	–	904	864	100	903		939	–	–	931	899	–	941	924
95	–	1033	960	1001	959	–	1.03	988	1	186	829	1050	899	–	909	869	109	911	1.01	945	–	–	945	924	–	946	939
94	–	1038	964	1001	963	–	1.04	992	1.01	188	833	1050	903	–	911	873	110	914	1.01	949	–	–	955	934	–	948	946
93	–	1041	968	1010	964	–	1.07	996	1.01	194	837	1052	908	–	914	876	115	917	1.02	953	–	–	954	942	–	947	948

TABLE A - 6

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 7 RUN NUMBER 8 DATE 6/10/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,\max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,\max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
100		433	.301	3.43	2.24	0.49			Jet A	34.1	34.1	299	.90	--		15.2	15.5	1.02		5.98	521	566		930	1074	1.29	.29	
102		684	.944	3.43	5.47	1.31				100.2	58.9	300	2.60	0.02		18.3	20.3	1.00		4.03	783	853		1254	1429	1.30	.31	88
103		801	1.693	3.43	9.13	2.11				199.6	30.5	300	1.13	0.52		21.9	22.0	1.00		4.13	983	1111		1485	1728	1.24	.36	92
109		432	.303	3.14	2.27	0.51			ERBS 12.8	29.4	29.4	300	0.65	--		13.0	16.3	1.02		5.29	507	546		842	944	1.18	.25	
110		433	.304	3.14	2.16	0.51				34.6	34.6	300	0.88	--		16.0	15.7	0.97		5.18	527	576		940	1074	1.21	.27	
111		433	.303	3.14	2.27	0.51				24.3	24.3	300	1.36	--		10.7	16.4	1.03		5.20	481	521		735	810	1.20	.25	73
107		615	1.109	2.59	7.18	1.62				92.1	57.7	301	2.48	0		12.8	20.2	1.05		4.89	691	759		1026	1175	1.24	.36	88
106		683	.944	2.46	5.64	1.25				100.8	59.4	301	2.55	0.02		17.9	20.6	1.03		4.60	803	875		1218	1397	1.23	.33	85
105		771	1.467	2.46	7.96	1.83				166.2	32.5	301	1.08	0.32		20.9	21.3	0.99		4.26	949	1077		1409	1640	1.22	.36	90
104		804	1.696	2.46	9.01	2.12				200.0	30.8	301	1.09	0.50		22.2	21.8	0.99		3.94	999	1133		1486	1748	1.24	.38	92

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-7 RUN NUMBER 8 DATE 6/10/81 SHEET 2

ID	MEASURED EMISSIONS							EMISSIONS CALCULATIONS						RATIOS						STOICHIOMETRY		COMMENTS	
READING	CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K	EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg	f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
100	223	3.22	10.59	30.2	4.3	.275	348	13.8	0.38	3.07	15.88	99.65	2.91	1.04	5.79	23.69	0		1.000				1
102	122	3.91	1.79	134.6	6.2	--	--	6.2	0.05	11.32	19.25	99.85	10.75	1.05	4.06	24.07	206.3		0.588				1
103	122	4.67	1.64	369.9	16.7	1.623	341	5.2	0.04	26.08	23.05	99.87	30.79	1.05	4.10	18.94	153.8		0.153				1
109	324	2.73	50.9	26.6	3.5	.156	330	23.7	2.14	3.20	13.38	99.26	3.09	1.03	5.09	24.31	0		1.000				1
110	294	3.28	16.51	37.3	2.6	.154	330	18.0	0.58	3.76	16.02	99.53	3.49	1.00	5.46	24.25	0		1.000				2
111	595	2.11	347.7	15.8	2.6	.188	330	54.6	18.27	2.38	10.65	97.14	2.31	.995	5.07	13.72	0		1.000			Blowout W_f = .130 g/s (f_m=5.72g/kg)	1
107	41	2.84	2.51	112.0	1.8	.222	335	2.9	0.10	13.07	13.79	99.92	12.27	1.08	4.39	24.13	469.0		0.630				1
106	93	3.83	1.94	144.2	3.1	.192	340	4.9	0.06	12.51	18.63	99.88	11.95	1.04	4.37	24.52	219.9		0.590				1
105	97	4.40	3.07	307.9	11.0	.241	351	4.5	0.08	23.24	21.47	99.89	26.10	1.03	4.34	20.63	155.3		0.195				1
104	116	4.69	2.51	393.9	13.6	.252	346	5.0	0.06	27.91	22.91	99.88	31.68	1.03	4.02	19.44	156.8		0.154				2

Emissions Sampling Mode

1. Ganged
2. Individual Rakes

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-7 RUN NUMBER 8 DATE 6/10/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K															
	OUTER LINER							INNER LINER								DOME
PANEL	1	1	3	3	5	5	OUTER	1	1	3	3	5	5	INNER	LINER	
ANGLE	0	6	0	6	0	6	AVG	0	6	0	6	0	6	AVG	AVG	
100	547	–	538	566	–	546	549	546	–	488	–	466	469	492	521	
102	775		786	853		848	816	805		726		739	735	751	783	
103	958		989	1111		1076	1034	1049		876		910	891	932	983	
109	503		517	546		546	528	527		479		465	469	485	507	
110	524		531	571		568	549	576		494		473	476	505	527	
111	472		476	510		521	495	493		462		456	460	468	481	
107	683		687	744		759	718	703		647		655	653	665	691	
106	798		803	875		875	838	833		739		754	746	768	803	
105	944		957	1077		1027	1001	1001		848		880	860	897	949	
104	982		1008	1133		1080	1051	1074		886		924	901	946	999	

TABLE A - 7

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 9 RUN NUMBER 11 DATE 3/7/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
153		431	.317	13.3	2.36	--	--		ERBS 12.8	36.1	36.1	301	.963	.006		15.3	15.7	1.05		4.39	538	618	--	786	1043	1.40	.72	
159		437	.296	15.7	2.46	0.47	--			35.0	35.0	300	.908	0		14.2	18.0	1.18		4.90	522	589	--	870	1091	1.21	.51	
154		615	1.118	18.1	7.24	1.50	--			91.7	59.3	303	2.518	.001		12.7	19.9	1.09		4.38	706	825	--	1097	1354	1.07	.53	
155		688	1.106	16.3	5.91	1.35	--			98.4	59.2	301	2.508	.002		16.7	19.8	1.01		2.40	835	980	--	1189	1489	1.28	.60	
156		684	.940	19.4	5.61	1.17	--			98.8	59.7	301	2.548	.011		17.6	20.4	1.06		4.21	810	930	--	1180	1460	1.27	.57	
157		773	1.469	31.1	8.19	1.71	--			165.5	42.7	301	1.097	.323		20.2	21.6	1.05		3.92	1010	1249	--	1361	1713	1.29	.60	
158		807	1.665	31.1	9.21	1.93	--			200.2	44.5	300	1.133	.516		21.7	22.3	1.07		3.95	1058	1315	--	1444	1802	1.22	.56	

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-8 RUN NUMBER 11 DATE 8/7/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
153		--	--	--	--	9.36	--	--		--	--	--	--	--	--		--	4.08	24.3	0		1.00				
159		991	3.19	32.6	33.7	5.54	.281	365		60.4	11.35	3.37	16.23	97.60	3.53		1.14	3.74	24.2	0		1.00				
154		53	2.57	12.9	83.1	1.49	1.067	403		4.17	0.58	10.74	12.43	99.85	9.96		0.98	3.94	24.6	813		.65				
155		49	3.91	10.4	164	2.57	1.017	376		2.56	0.31	13.92	19.03	99.91	12.12		1.14	2.51	24.7	626		.60				
156		58	3.90	7.0	142	2.37	.900	371		3.01	0.21	12.13	18.98	99.91	11.49		1.08	4.00	24.7	542		.60				
157		82	4.44	6.7	297	5.09	1.413	367		3.71	0.17	22.19	21.69	99.90	25.26		1.07	3.77	26.9	143		.26				
158		108	4.84	7.2	381	6.74	1.599	371		4.50	0.17	26.11	23.68	99.88	30.41		1.09	3.71	27.5	143		.22				

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-8 RUN NUMBER 11 DATE 8/7/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																							
	OUTER LINER									INNER LINER								DOME						
PANEL	1	1	1	1	3	3	5	5	AVG	1	1	3	3	5	5	AVG	AVG	CUP 4	CUP 4	CUP 5	CUP 5	DOME	DOME	AVG
ANGLE	-3	0	3	6	0	6	0	6	OUTER	0	6	0	6	0	6	INNER	LINER	SP 1	SP 2	SP 1	SP 2	1	2	DOME
153	570	555	440	618	576	594	576	587	565	–	535	398	–	480	507	485	538				483	483	498	488
159	534	520	420	579	561	569	576	589	544		525	405		481	509	480	522				--	480	492	486
154	760	735	551	825	798	736	774	754	742		731	496		648	665	635	706				871	680	724	758
155	880	855	630	980	908	953	888	923	877		889	559		765	795	752	835				1018	815	839	891
156	839	818	605	930	883	924	880	910	849		851	552		754	779	734	810				972	798	813	861
157	1120	1071	755	1249	1132	1149	1058	1074	1076		1071	628		890	925	879	1010				--	926	988	157
158	1164	1116	780	1315	1193	1224	1113	1134	1130		1113	655		929	957	914	1058				--	983	1033	1008

TABLE A - 8

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 9 **RUN NUMBER** 22 **DATE** 12/14/81 **SHEET** 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
297	434	.301	2.03	2.24	0.48	--	ERBS 12.8	24.2	24.2	285	--	--	10.8	16.4	1.03	5.05	481	528	--	717	834	1.29	0.41	67
298	433	.303	2.22	2.17	0.48			28.7	28.7	285	--	--	13.3	15.6	0.98	5.26	509	566	--	779	940	1.32	0.47	68
299	429	.303	2.05	2.21	0.48			35.6	35.6	285	0.91		16.1	15.8	1.00	5.87	526	606	--	898	1061	1.22	0.35	--
300	431	.304	--	2.19	0.48			41.7	41.7	285	1.21		19.0	15.6	0.98	5.52	533	614	--	965	1139	1.24	0.33	--
301	457	.377	2.84	2.59	0.67			43.0	43.0	286	1.28		16.6	16.3	0.96	6.30	537	618	77.8	908	1059	1.21	0.33	--
302	459	.379	2.14	3.26	0.67			34.3	34.3	286	0.86		10.5	19.7	1.21	6.47	507	556	50.8	786	883	1.20	0.30	--
303	459	.381	1.99	3.06	0.66			28.8	28.8	286	0.61		9.4	18.6	1.13	5.92	196	543	46.1	723	794	1.20	0.27	--
304	612	1.110	1.30	7.09	1.65			94.4	45.7	286	2.50		13.3	19.9	1.04	4.86	675	742	237.4	1015	1182	1.23	0.41	83
305	684	.939	1.00	5.36	1.38			102.5	60.9	286	2.51		19.1	20.3	0.98	4.22	776	856	345.6	1241	1468	1.23	0.41	82
307	773	2.436	0.96	13.01	3.12			282.3	64.7	284	2.85		21.7	21.2	0.98	3.76	900	1020	--	1423	1695	1.20	0.42	89
308	806	2.788	1.06	14.32	3.47	--		344.3	64.5	283	2.91	--	24.1	21.2	0.96	3.45	941	1076	--	1516	1819	1.21	0.43	89

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-9 RUN NUMBER 22 DATE 12/14/81 SHEET

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_c	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
297		606	1.91	459	11.[illegible]	--	.228	363		60.8	26.37	1.84	9.73	96.30	1.75		0.90	4.73	--			0.36				1
298		358	2.32	180	19.6	0.8	.248	364		30.6	8.81	2.76	11.45	98.52	2.49		0.86	5.51	--	--		0.44				1
299		338	3.31	64	31.4	2.0	.255	366		20.5	2.22	3.12	16.23	99.33	2.90		1.01	5.91	24.5			0.54				3
300		353	3.46	29	35.9	4.9	.248	354		20.4	0.96	3.42	16.95	99.44	3.00		0.89	5.71	24.9			0.63			Blowout @ 15.7 g/s f=7.19 g/kg	1
301		215	2.81	64	33.4	5.7	.255	376		15.4	2.61	3.92	13.72	99.41	--		0.83	6.77	25.0			0.55				1
302		725	1.96	361	13.4	5.2	.262	377		71.2	20.28	2.16	9.95	96.58	--		0.95	4.42	24.4			0.35				1
303		894	1.73	625	8.9	4.0	.262	376		96.5	38.63	1.58	9.04	94.40	--		0.96	4.62	24.2			0.31				1
304		51	2.51	103	18.8	1.7	.538	413		4.1	4.71	0.40	12.18	99.50	9.52		0.92	4.51	25.4			0.44				1
305		56	3.23	19	136.6	5.9	.434	408		3.5	0.69	4.03	15.69	99.86	12.75		0.82	4.37	25.3			0.64				1
307		41	3.74	3*	337.3	17.9	1.000	424		2.2	[illegible]	[illegible]	18.15	99.94	25.97		0.84	3.94	25.2			0.72				1
308		83	5.81	3.7	592.6	--	.011	421		2.9	[illegible]	[illegible]	28.52	99.93	29.60		1.18	3.75	24.9			0.80			**	1

* Corrected to Stable Value

** Individual Samples on Two of Four Rakes

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-9 RUN NUMBER 22 DATE 12/14/81 SHEET

ID COMBUSTOR METAL TEMPERATURES, K

	OUTER LINER											INNER LINER						DOME						
PANEL	0	0	0	1	1	1	1	3	3	5	5	1	1	3	3	5	5	SP 4	SP 4	SP 5	SP 5	OUTER	INNER	AVG
ANGLE	0	3	6	-3	0	3	6	0	6	0	6	0	6	0	6	0	6	OUTER	INNER	OUTER	INNER	AVG	AVG	LINER
297	470	476	–	478	479	472	508	480	–	515	528	–	481	450	476	449	465	480	1188	–	1135	490	464	481
298	486	488	–	531	531	503	566	520	–	536	537	–	516	458	506	456	491	513	1018	–	1003	522	485	509
299	504	504	–	535	544	529	606	524	–	548	558		546	461	530	461	509	435	434	–	1090	539	501	526
300	514	505	–	553	566	529	614	534	–	557	571		545	464	529	466	509	430	430	–	1068	549	502	533
301	512	509	–	555	555	530	618	543	–	565	581		539	482	531	483	515	456	456	–	–	552	510	537
302	493	493	–	510	509	498	550	510	–	542	556		498	474	499	474	489	457	457	–	–	518	486	507
303	489	485	–	502	496	481	510	505	–	535	543		486	471	488	471	483	458	458	–	–	505	480	496
304	665	664	–	678	676	650	698	683	–	738	742		664	633	665	635	653	610	610	–	–	688	650	675
305	773	768	–	776	776	749	822	785	–	840	856		768	716	768	721	741	679	679	–	–	794	743	776
307	880	873	–	899	886	852	991	917	–	975	1020		906	815	897	823	864	769	770	–	–	922	861	900
308	915	911	–	938	922	889	1040	954	–	1023	1076		948	851	941	861	909	803	803	–	–	963	902	941

Table A-9. Configuration S-9 Subatmospheric Test Results.

Reading Number	Fuel Type	Sector Combustor Inlet Conditions					Operating* Mode
		Air Pressure, mPa	Airflow, kg/s	Fuel Flow, g/s	Temperature, K	Air Temperature, K	
281	Jet A	0.042	0.24	11.5	279	279	SS
282		0.041	0.21	-	279	-	B
279		0.040	0.37	11.5	279	281	SS
280		0.035	0.37	-	278	-	B
277		0.048	0.48	11.7	279	281	SS
278		0.040	0.54	-	278	-	B
275		0.065	0.08	12.3	280	278	L/O
276		0.059	0.83	-	279	-	B
295	ERBS 12.8	0.063	0.35	11.7	277	282	L/O
296		0.043	0.38	-	277	-	B
293		0.054	0.52	11.6	277	283	SS
294		0.048	0.53	-	277	-	B
291		0.069	0.81	11.7	277	282	L/O
292		0.066	0.83	-	277	-	B
283	ERBS 11.8	0.045	0.22	12.2	279	282	Marginal
284		0.043	0.36	-	278	-	B
285		0.048	0.33	11.7	278	282	SS
286		0.044	0.33	-	278	-	B
287		0.052	0.47	11.7	277	282	SS
288		0.047	0.52	-	277	-	B
289		0.073	0.78	11.7	277	282	L/O
290		0.070	0.82	-	277	-	B

* SS = steady state; B = blowout; L/O = lightoff

TABLE A - 10

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 10 RUN NUMBER 25 & 26 DATE 2/12,15,16/81 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	$\bar{T}_L$ - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	$\bar{T}_{39}$ - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
342	431	.300	1.8	2.11	0.48	--	ERBS 12.8	35.5	35.5	286	0.780	--	16.8	15.4	2.98	3.95	548	608	108	973	1180	1.14	.38	86
343	619	1.097	1.3	7.52	1.65	--		93.6	59.3	295	2.359	0.003	12.4	21.4	1.12	5.03	701	761	238	998	1200	1.26	.51	84
344	681	.934	1.3	5.84	1.45	--		100.6	60.2	294	2.393	0.012	17.2	22.0	1.07	5.39	782	836	286	1144	1390	1.23	.53	77
345	766	2.421	1.9	14.46	2.90	--		279.8	62.9	294	2.782	0.803	19.4	22.8	1.09	4.80	918	998	--	1323	1595	1.23	.49	84
346	804	2.784	1.4	15.01	3.33	--		305.1	58.1	294	2.314	1.046	20.3	21.9	1.01	4.58	959	1023	643	1349	1599	1.25	.46	--
347	803	2.571	1.4	14.66	3.08	--		284.0	54.3	294	2.022	0.912	19.4	22.9	1.06	4.70	960	1024	612	1352	1626	1.22	.50	--
348	806	2.579	1.4	13.34	3.11	--		347.5	66.3	294	2.987	1.358	26.1	21.3	0.96	4.46	988	1074	605	1465	1783	1.26	.48	--
349	806	2.579	1.4	14.04	3.10	--		312.9	59.4	294	2.469	1.099	22.3	22.2	1.02	4.51	976	1050	621	1407	1720	1.27	.52	81
341	432	.299	1.8	2.15	0.47	--	ERBS 11.8	35.7	35.7	285	0.760	--	16.6	15.7	0.98	3.69	557	626	139	963	1151	1.14	.36	85
351	685	.931	1.4	6.10	1.41	--		101.8	60.4	286	2.299	0.029	16.7	22.8	1.13	5.93	791	842	334	1156	1404	1.23	.53	80
350	806	2.576	1.4	14.34	3.08	--		315.4	59.6	285	2.418	1.091	22.0	22.6	1.04	4.69	984	1053	632	1401	1715	1.25	.53	81
340	432	.301	1.8	2.10	0.49	--	12.3	35.6	35.6	284	0.759	--	16.9	15.4	0.95	3.91	556	623	132	978	1170	1.14	.35	86
352	690	.933	1.4	5.79	1.38	--		100.9	59.8	295	2.321	0.025	17.4	21.9	1.07	5.60	793	846	305	1158	1401	1.24	.52	77

TABLE A - 10

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S - 10 RUN NUMBER 25 & 26 DATE 2/12,15,16/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
353		793	2.579	1.5	14.07	2.98	--		ERBS 12.3	315.6	60.6	293	2.428	1.094		22.4	21.7	1.01		4.51	974	1044	--	1399	1698	1.25	.49	81
354		800		1.5	13.49	3.06	--			315.4	59.9	293	2.432	1.092		23.4	21.2	0.97		4.51	977	1049	--	1408	1699	1.25	.48	78
339		432	.297	1.9	2.10	.48	--		Jet A	35.4	35.4	287	0.780	--		16.8	15.6	0.97		4.33	540	602	79	965	1157	1.16	.36	85
357		684	.936	1.5	5.78	1.40	--			100.9	59.4	292	2.432	1.092		17.4	21.7	1.06		4.33	774	837	--	1169	1405	1.22	.49	78
356		775	2.418	1.5	13.30	2.85	--			281.0	63.3	291	2.825	0.825		21.1	21.4	1.01		4.64	289	1001	--	1349	1631	1.26	.49	80
355		806	2.577	1.5	14.06	3.08	--			316.1	59.7	293	2.391	0.023		22.5	22.2	1.02		4.33	971	1051	--	1426	1713	1.24	.46	82

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-10 **RUN NUMBER** 25 & 26 **DATE** 2/12,15,16/82 **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
342		302	4.01	4.4	48.1	5.5	.241	368		15.2	0.13	3.96	19.65	99.63	3.56		1.17	4.26	26.5	--	--	1.000	.56			1
342		341	4.13	4.9	48.7	--	--	--		16.6	0.14	3.89	20.24	99.60	3.50		1.20	--	--	--	--	--	--			3
343		30	2.87	3.2	112.0	6.9	.758	411		2.1	0.13	12.98	13.88	99.94	12.39		1.12	4.00	25.5	--	1.19	.634	.41			1
344		57	3.58	2.6	153.4	3.7	.614	408		3.2	0.08	14.23	17.41	99.92	14.30		1.01	4.69	25.6	--	1.30	.598	.57			1
345		33	4.25	4.2	405.2	8.1	1.207	425		1.6	0.11	31.70	20.70	99.95	31.60		1.07	4.06	24.8	159.	51.1	9 .225	.65			1
346		24	4.16	4.1	491.0	13.8	1.317	427		1.2	0.11	39.25	20.25	99.96	36.03		1.00	4.53	25.2	158.	5 --	.190	.69			1
347		27	4.31	3.5	507.9	8.7	1.310	426		1.3	0.09	39.18	20.99	99.96	38.96		1.08	4.16	25.2	158.	5 --	.192	.65			1
348		55	5.22	3.4	553.9	15.8	1.303	425		2.1	0.08	35.30	25.52	99.94	32.02		0.98	4.78	25.3	159.	1 --	.191	.87			1
349		38	4.73	3.5	528.2	--	1.241	425		1.6	0.08	37.16	23.07	99.95	35.12		1.03	4.36	24.9	159.	31.2	3 .190	.74			1
349		66	4.87	5.0	543.1	9.3	--	--		2.7	0.12	37.10	23.77	99.93	35.07		1.07	--	--	--	--	--	--			3
341		299	4.06	5.0	53.0	5.8	.241	367		15.0	0.14	4.38	19.57	99.63	4.00		1.18	3.82	27.0	--	--	1.000	.55			1
351		51	3.59	6.7	152.1	3.0	.531	398		2.9	0.22	14.26	17.20	99.91	14.70		1.03	4.66	26.3	159.	51.2	5 .593	.56		Blowout W_f=13.2g/s F_m=6.17g/kg	1
350		47	4.70	4.8	537.8	10.6	1.269	423		2.1	0.12	38.51	22.61	99.94	37.09		1.03	4.34	25.3	161.	41.2	3 .189	.73			1

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-10 RUN NUMBER 25 & 26 DATE 2/12,15,16/82 SHEET 2 Cont'd.

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS						
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg	
340		317	4.20	7.9	52.6	5.9	.283	369		15.30	0.22	4.17	20.41	99.62	3.71	
352		51	3.60	4.3	156.7	1.0	.531	407		2.90	0.14	14.58	17.34	99.92	14.04	
353		43	4.74	3.0	491.0	--	--	--		1.90	0.07	34.74	22.91	99.95	34.36	
354		44	4.69	3.1	511.9	6.9	1.310	421		1.90	0.08	36.62	22.65	99.95	34.21	
339		286	3.90	6.7	43.7	4.0	.290	364		14.60	0.20	3.67	19.28	99.64	3.33	
357		52	3.57	1.3	145.5	1.7	.483	408		2.90	0.04	13.41	17.53	99.93	13.19	
356		35	4.26	1.8	419.8	5.6	1.138	424		1.64	0.05	32.50	20.95	99.96	29.00	
355		76	5.02	2.3	528.7	15.5	1.193	425		3.03	0.05	34.70	24.80	99.92	32.83	

ID	RATIOS						STOICHIOMETRY		COMMENTS	
READING	f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
340	1.21	4.29	27.0	--	--	1.000	.56		Blowout W_f=13.5 g/s F_m=5.63 g/kg	1
352	1.00	4.87	25.9	171.	31.30	.593	.58			1
353	1.02	4.42	25.6	160.	61.23	.192	.75			1
354	0.10	4.78	25.3	161.	11.28	.190	.78			1
339	1.15	4.61	26.0	--	--	1.000	.56		Blowout W_f=11.8 g/s F_m=5.63 g/kg	1
357	1.01	4.70	25.3	179.	01.28	--	.58			1
356	0.99	4.58	24.8	157.	61.25	.225	.70			1
355	1.10	4.17	25.2	161.	71.22	.189	.75			1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-10 RUN NUMBER 25 & 26 DATE 2/12, 15, 16/82 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																						
	OUTER LINER											INNER LINER						DOME					
PANEL	0	0	0	1	1	1	1	3	3	5	5	1	1	3	3	5	5	OUTER	INNER	AVG	OUTER	INNER	AVG
ANGLE	0	3	6	-3	0	3	6	0	6	0	6	0	6	0	6	0	6			DOME	AVG	AVG	LINER
342	528	-	598	604	608	458	-	578	463	558	569	583	588	525	543	-	472	538	610	574	552	542	548
343	668	-	708	723	693	-	718	707	-	733	761	689	-	684	687	-	646	672	760	716	714	677	701
344	754	-	790	811	776	-	799	791	-	819	836	769	-	759	764	-	713	752	848	800	797	751	782
345	888	-	950	963	931	-	969	962	-	961	998	813	-	884	889	-	812	905	1020	963	953	850	918
346	924	-	973	1010	971	-	985	1000	-	996	1023	938	-	914	923	-	845	951	1066	1009	985	905	959
347	923	-	979	1013	978	-	983	1006	-	997	1024	939	-	914	924	-	844	957	1063	1010	988	905	960
348	937	-	1004	1033	993	-	1027	1042	-	1039	1074	957	-	935	949	-	863	983	1058	1021	1019	926	988
349	936	-	994	1029	987	-	1011	1026	-	1018	1050	950	-	925	938	-	853	971	1064	1018	1006	917	976
341	541	-	612	616	626	468	-	584	469	561	572	594	597	531	549	-	473	550	620	585	561	549	557
351	772	-	804	808	783	-	811	605	-	828	842	779	-	765	774	-	721	778	868	823	807	760	791
350	946	-	1008	1031	993	-	1031	1029	-	1023	1053	958	-	938	946	-	854	990	1065	1028	1014	924	984
340	537	-	606	617	623	465	-	586	472	563	573	590	596	534	551	-	474	549	627	588	560	549	556
352	774	-	805	810	782	-	809	804	-	831	846	786	-	771	778	-	725	778	871	825	808	765	793
353	926	-	995	1014	975	-	1029	1012	-	1005	1044	945	-	-	931	-	841	969	1063	1016	1000	906	974
354	936	-	1000	1024	985	-	1035	1020	-	1015	1049	954	-	914	941	-	848	979	1069	1024	1008	914	977

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION S-10 RUN NUMBER 25 & 26 DATE 2/12, 15, 16/82 SHEET 3 CONT'D.

ID	COMBUSTOR METAL TEMPERATURES, K																						
	OUTER LINER											INNER LINER						DOME					
PANEL	0	0	0	1	1	1	1	3	3	5	5	1	1	3	3	5	5	OUTER	INNER	AVG	OUTER	INNER	AVG
ANGLE	0	3	6	-3	0	3	6	0	6	0	6	0	6	0	6	0	6			DOME	AVG	AVG	LINER
339	522	–	590	596	602	449	–	570	456	553	564	569	571	518	534	–	467	533	609	571	545	532	540
357	743		776	788	762	–	792	–	–	821	837	764	–	756	762		718	745	839	792	788	750	774
356	888		944	964	934		969	968		970	1001	905		886	894		818	910	1008	959	955	876	928
355	924		984	1013	976		1013	1020		1016	1051	940		923	934		852	965	1060	1013	1000	912	971

TABLE A - 11

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D1 RUN NUMBER 1 DATE 3/25/81 SHEET 1

ID		COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
4		430	.305	0.81	2.20	0.50	--	Jet A	0.024	0.024	286	0.27	--	11.1	15.72	0.98	4.42	468	646	--	918	1246	1.67	0.67	112
5		430	.305	0.81	2.19	0.49	--		0.024	0.024	286	0.27	--	11.1	15.66	0.98	4.39	468	648	--	916	1233	1.66	0.66	111
6	IDL	431	.305	0.81	2.19	0.49	--		0.024	0.024	286	0.27	--	11.1	15.70	0.98	4.36	468	649	--	913	1234	1.67	0.67	111
7		430	.305	0.82	2.07	0.49	--		0.018	0.018	286	0.18	--	8.8	14.93	0.92	3.81	460	613	--	764	1118	1.83	1.06	95
8		431	.303	0.82	2.12	0.49	--		0.030	0.030	293	0.36	--	14.0	15.41	0.96	4.39	473	679	--	923	1407	1.80	0.98	--
9	APP	611	1.106	0.11	7.15	1.61	--		0.093	0.093	296	2.77	--	12.9	20.04	1.05	4.75	671	876	--	1188	1700	1.62	0.89	121
12	CLI	770	1.461	0.11	8.26	1.82	--		0.166	0.034	298	0.37	0.81	20.1	21.95	1.03	4.83	887	1088	--	1384	1579	1.16	0.32	89
13		803	1.687	0.12	9.07	2.06	--		0.201	0.031	298	0.31	1.34	22.1	21.93	1.00	4.59	959	1173	--	1473	1709	1.18	0.35	75
14		803	1.688	0.11	9.06	2.06	--		0.201	0.031	298	0.31	1.35	22.2	21.87	1.00	4.61	948	1163	--	1514	1709	1.27	0.27	95
15	T/O	801	1.674	0.09	9.07	2.04	--		0.202	0.043	296	0.57	1.19	22.3	21.99	1.01	4.43	954	1150	--	1514	1693	1.25	0.25	15
16	T/O	804	1.677	0.07	9.06	2.10	--	ERBS 12.8	0.201	0.042	295	0.54	1.15	22.7	22.10	1.01	4.55	953	1150	--	1500	1664	1.24	0.24	92
17	CLI	773	1.469	0.07	8.30	1.86	--		0.163	0.036	295	0.39	0.73	19.7	22.13	1.03	4.95	904	1067	--	1398	1552	1.25	0.25	93
18	CRU	685	0.935	0.08	5.57	1.23	--		0.098	0.020	295	0.14	0.27	17.6	20.60	1.03	5.12	784	908	--	1237	1389	1.27	0.27	89
19		684	0.932	0.08	5.67	1.24	--		0.098	0.020	294	0.13	0.27	17.4	20.98	1.05	5.13	769	903	--	1226	1366	1.26	0.26	89

TABLE A - 11

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D1 RUN NUMBER 1 DATE 3/25/81 SHEET 2

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
20	APP	614	1.094	0.08	7.20	1.54	--			0.093	0.093	295	2.69	--		12.9	20.28	1.07		4.88	686	855	--	1057	1669	2.38	1.38	94
21	IDL	433	0.300	0.08	2.20	0.50	--		ERBS 12.8	0.024	0.024	294	0.21	--		11.2	16.59	0.99		4.89	477	636	--	798	1241	2.21	1.21	84

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D1 RUN NUMBER 1 DATE 3/25/81 SHEET 1

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
4		744	2.08	424	14.4	--	.221	348		68.0	22.20	2.16	10.69	96.48	--		0.96	4.60	30.7	--	0.86	1.000	0	0.66	Exit T/C Rake A Only	1
5		674	2.43	305	17.1	--	.124	358		53.6	13.89	2.23	12.32	97.55	--		1.11	4.57	30.6	--	0.88	1.000	0	0.66	Exit T/C Rake A Only	2
6		714	2.58	261	12.9	--	.159	361		53.4	11.24	1.64	13.10	97.78	--		1.18	4.54	30.7	--	0.88	1.000	0	0.66	Exit R/C Rake A Only	3
7		726	1.84	524	11.6	--	.159	350		74.1	30.65	1.94	9.57	95.61	--		1.09	4.50	28.3	--	1.01	1.000	0	0.53		1
8		1106	2.74	202	21.5	--	.159	356		77.5	8.12	2.47	13.99	97.48	--		1.00	4.76	32.5	--	--	1.000	0	0.84		1
8R		1090	2.71	204	20.6	--	.159	356		77.1	8.25	2.39	13.88	97.48	--		0.99	4.76	32.5	--	--	1.000	0	0.84		2
9		162	2.53	6.5	77.7	--	.276	389		12.8	0.29	10.09	12.39	99.68	9.11		0.96	4.31	36.6	--	0.82	1.000	0	0.77		2
12		302	4.06	115.1	122.5	6.8	.324	391		14.8	3.23	9.84	20.17	99.37	11.00		1.00	4.55	37.1	101.4	1.12	0.205	0.52	0.25		1
12R		296	4.08	68.1	125.7	--	.324	391		14.4	1.90	10.07	20.24	99.50	11.26		1.01	4.55	37.1	101.4	1.12	0.205	0.52	0.25		2
13		303	4.49	23.9	183.5	4.0	.262	366		13.5	0.61	13.39	22.26	99.63	14.68		1.01	4.59	36.7	101.1	1.11	0.155	0.56	0.20		2
14		320	4.46	16.5	181.3	--	.696	397		14.3	0.37	13.30	22.04	99.63	14.65		0.99	4.61	37.0	101.0	1.05	0.154	0.61	0.20		3
15		125	4.60	6.8	182.4	2.6	.572	395		5.45	0.17	13.05	22.71	99.86	14.51		1.02	4.34	37.1	101.1	1.05	0.205	0.57	0.27		2
16		118	4.47	5.8	181.8	4.9	.565	393		5.35	0.15	13.48	21.86	99.86	14.87		0.98	4.46	37.7	102.7	1.09	0.208	0.60	0.29		2
17		252	3.15	6.8	130.3	2.1	.558	391		12.9	0.20	10.10	19.33	99.68	12.03		0.98	4.67	37.5	102.1	1.07	0.180	0.51	0.26		2
18		1294	3.48	13.1	61.6	--	.416	381		74.8	4.70	5.23	17.60	97.84	5.07		1.00	4.63	35.1	102.3	1.10	0.204	0.47	0.22		4

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D1 RUN NUMBER 1 DATE 3/25/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
19		--	--	--	--	--	--	--		--	--	--	--	--	--		--	4.65	36.5	03.7	--	0.202	0.46	0.22	Pilot Stage Out	-
20		188	3.12	33	101.6	--	.262	388		12.2	1.23	10.8	15.19	99.61	9.82		1.18	4.26	37.3	--	1.06	1.000	0	0.79		2
21		820	2.47	368	16.0	--	.159	367		64.2	16.53	2.08	12.50	97.06	--		1.12	4.99	37.2	--	1.16	--	0	0.69		1

C-4

Sampling Mode

1 - Ganged
2 - Individual Rakes
3 - Individual Elements
4 - Individual Rakes - B and C Only

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-1 RUN NUMBER 1 DATE 3/25/81 SHEET 1

ID COMBUSTOR METAL TEMPERATURES, K

	OUTER LINER							INNER LINER											DOME		AVG
PANEL	1	1	1	5	5	CBI	CBI	1	1	1	2	3	3	4	CBI	CBI	PILOT	PILOT	MAIN	MAIN	
ANGLE	0	3	6	0	6	0	6	0	3	6	0	0	6	3	0	6	SP O	SP I	SP O	SP I	
4	572	485	529	646	–	449	456	431	431	–	433	432	435	435	435	–	–	461	429	429	468
5	570	483	528	648	–	448	455	430	431	–	433	432	436	435	435	–	–	461	430	430	468
6	570	483	526	649	–	448	455	430	431	–	433	433	436	436	435	–	–	461	431	431	468
7	528	478	506	613	–	446	449	430	430	–	431	431	434	434	432	–	–	456	430	430	460
8	589	477	525	679	–	453	460	432	431	–	434	433	438	436	436	–	–	476	433	433	473
9	808	711	743	876	–	651	641	614	615	–	618	617	626	624	619	–	–	740	613	613	671
12	895	841	835	874	–	644	786	953	938	–	1088	980	1054	995	871	–	–	806	811	820	887
13	918	868	869	903	–	801	817	1089	1163	–	1173	1053	1133	1062	920	–	–	838	857	875	959
14	916	867	871	902	–	818	816	1081	1163	–	–	1054	1133	1063	926	–	–	836	858	875	945
15	945	880	882	924	–	774	819	1070	1143	–	1150	1043	1118	1050	915	–	–	845	853	865	954
16	942	879	886	925	–	771	822	1040	1116	–	1150	1044	1115	1052	930	–	–	846	860	866	953
17	905	844	850	881	–	795	790	949	1046	–	1067	978	1045	989	878	–	–	813	819	824	904
18	794	737	739	769	–	706	700	778	845	–	908	858	903	873	784	–	–	713	730	722	784
19	693	689	731	730	–	688	695	773	839	–	903	849	897	869	784	–	–	713	728	720	769
20	822	735	798	855	–	663	651	619	618	–	631	629	653	648	623	–	–	784	641	616	686
21	591	493	571	636	–	458	461	434	434	–	441	440	450	450	439	–	–	467	436	435	477

TABLE A - 12

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-2 RUN NUMBER 9 DATE 6/17/81 SHEET 1

ID: READING	ID	COMBUSTOR AIRFLOW: T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL FLOW: FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	CALCULATIONS: f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	COMBUSTOR PERFORMANCE: $\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
112		433	.303	2.36	2.25	.496	--	Jet A	17.5	17.5	298	0.10	--	7.8	16.2	1.02	5.09	483	609	--	651	910	1.62	1.18	70
113	IDL	431	.303	2.36	2.09	.502	--	↓	23.3	23.3	298	0.19	--	11.1	15.2	0.94	4.23	511	736	--	788	1154	1.62	1.02	82
114		434	.299	2.36	2.26	.478	--		28.9	28.9	298	0.29	--	12.8	16.4	1.03	5.69	523	760	--	843	1116	1.66	0.67	--
115	APP	614	1.111	1.67	7.15	1.532	--		93.3	93.3	295	2.92	--	13.1	19.8	1.05	5.27	712	964	87.0	1037	1493	0.54	1.08	87
116		613	1.107	1.67	7.24	1.515	--		92.7	47.3	294	0.74	0.11	12.8	20.1	1.06	5.45	706	797	67.7	909	1088	1.18	0.60	62
117	CRO	683	.947	1.67	5.62	1.234	--		99.9	27.0	294	0.24	0.36	17.8	20.5	1.02	4.83	843	945	41.9	1032	1306	1.79	0.79	55
118		682	.948	1.67	5.73	1.238	--		99.3	40.9	294	0.55	0.22	17.3	20.8	1.04	4.89	832	900	72.0	1068	1225	1.32	0.41	63
119	CLI	768	1.470	1.67	7.97	1.833	--		165.4	34.6	294	0.41	1.22	20.8	21.2	0.99	4.66	969	1135	61.5	1184	1556	1.90	0.90	59
120		799	1.686	1.67	9.05	2.046	--		201.4	42.8	295	0.59	1.82	22.2	21.8	1.00	4.77	996	1220	75.3	1281	1662	1.79	0.79	65
121	T/O	803	1.686	1.67	8.99	2.046	--	↓	199.9	61.4	297	1.29	1.39	22.2	21.8	0.99	4.86	1001	1186	108.7	1291	1579	1.59	0.59	65
124	IDL	432	.302	1.67	2.23	4.99	--	ERBS 12.3	23.9	23.9	298	0.20	--	10.7	16.1	1.01	4.93	508	729	0	758	1069	1.71	0.95	--
123	CRU	685	.938	1.67	5.52	1.238	--	↓	98.7	26.0	297	0.23	0.36	17.9	20.4	1.01	4.70	845	938	45.0	1086	1349	1.66	0.66	--
122	T/O	794	1.685	2.06	9.19	2.046	--	↓	201.6	62.4	299	1.23	1.33	21.9	21.9	1.01	4.78	998	1171	119.3	1277	1566	1.60	0.60	--
125	IDL	429	.304	2.04	2.39	.499	--	ERBS 12.8	23.7	23.7	299	0.19	--	9.9	16.9	1.07	4.99	501	745	0	745	1066	1.64	1.02	82

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-2 . **RUN NUMBER** 9 **DATE** 6/18/81 **SHEET** 2

READING	ID	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
		COMBUSTOR AIRFLOW						**FUEL FLOW**						**CALCULATIONS**			**COMBUSTOR PERFORMANCE**								
126	APP	610	1.108	1.95	7.15	1.569	--	↓	92.5	92.5	303	2.87	--	12.9	19.9	1.05	5.35	723	976	52.4	1036	1417	1.46	0.90	90
127	CRU	683	.941	2.08	5.55	1.229	--	ERBS 12.8	98.9	26.3	301	0.24	0.38	17.8	20.4	1.01	4.69	845	950	41.8	1069	1347	1.72	0.72	62
128	CLI	773	1.467	1.87	8.32	1.796	--	↓	167.0	36.6	304	0.43	1.29	20.1	22.1	1.04	4.63	969	1122	59.2	1223	1624	1.89	0.89	66
129	T/O	801	1.687	1.85	9.22	2.068	--	↓	200.7	62.5	304	1.27	1.45	21.8	22.2	1.02	4.58	1013	1164	109.4	1296	1611	1.64	0.64	68
132	IDL	438	.309	2.15	2.15	0.485	--	ERBS 11.8	23.2	23.2	300	0.18	--	10.8	15.8	0.98	5.14	509	705	--	743	1014	1.65	0.89	--
131	CRU	683	.943	2.05	5.64	1.255	--	↓	98.5	25.8	301	0.22	0.37	17.4	20.6	1.03	4.88	836	926	--	1033	1296	1.75	0.75	--
130	T/O	803	1.686	1.91	9.04	2.046	--	↓	199.5	61.9	304	1.28	1.40	22.1	21.8	1.00	4.62	1014	1153	116.2	1290	1591	1.62	0.62	--

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-2 RUN NUMBER 9 DATE 6/17/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
112		654	1.76	550	9.1	--	.269	338		69.8	33.61	1.60	9.15	95.45	1.51		1.17	4.93	36.3	--		1.00	0	0.54		1
113		495	2.36	392	18.6	3.4	.192	360		40.6	18.45	2.51	11.92	97.45	2.24		1.07	4.80	35.4	--		1.00	0	0.77		2
114		837	2.59	428	20.5	3.4	.188	383		61.8	18.10	2.48	13.28	96.98	2.36		1.04	5.32	35.3	--		1.00	0	0.88	Blowout W_f=9.20 g/s F_m=4.07 g/kg	1
115		181	2.50	6.8	78.2	--	.189	408		14.5	0.31	10.25	12.26	99.63	9.35		0.94	4.80	36.0	--		1.00	0	0.90		1
116		1689	2.52	1861	23.3	5.1	.190	408		118.0	74.50	2.68	14.03	90.77	2.49		1.10	4.80	36.2	90.1		.51	0.20	0.45		1
117		421	4.00	55	67.0	5.2	.187	400		20.8	1.57	5.45	19.91	99.38	5.08		1.12	4.63	36.0	79.7		.27	0.42	0.33		1
118		367	4.02	40	72.1	--	.185	405		18.2	1.13	5.86	19.95	99.48	5.57		.15	4.53	35.6	77.9		.41	0.33	0.49		1
119		208	4.76	11	179	4.2	.251	415		8.7	0.27	12.37	23.58	99.77	13.87		1.13	4.78	35.6	77.9		.21	0.53	0.30		1
120		172	5.11	12	249	4.5	.243	412		6.7	0.27	16.03	25.31	99.82	18.29		1.14	4.78	36.6	77.4		.21	0.56	0.32		3
121		71	5.02	7.9	242	3.7	.264	417		2.9	0.18	15.86	24.81	99.92	17.76		1.12	4.91	35.7	77.4		.31	0.49	0.47		1
124		591	2.44	280	22.2	8.7	.162	370		47.8	12.97	2.95	12.09	97.76	2.77		1.13	4.84	35.4	--		1.00	0	0.72	Blowout W_f=8.06 g/s F_m=3.62 g/kg	1
123		444	4.27	25	85.3	4.5	.201	410		21.0	0.68	6.63	20.82	99.44	6.12		1.16	4.58	35.9	80.2		.26	0.42	0.31		1
122		65	5.16	5.2	250	3.7	.264	414		2.6	0.12	16.22	25.01	99.93	19.24		1.14	4.69	37.0	79.5		.31	0.48	0.46		1
125		588	2.39	247	20.2	5.5	.166	368		48.1	11.57	2.71	11.96	97.87	2.68		1.21	4.37	35.4	--		1.00	0	0.68	Blowout W_f=9.45 g/s F_m=3.96 g/kg	1
126		196	2.70	15	92.0	2.3	.217	377		14.6	0.64	11.24	13.17	99.60	10.49		1.02	4.87	36.0	--		1.00	0	0.88		1

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-3 **RUN NUMBER** 14 **DATE** 9/4/81 **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
127		434	4.27	141*	81.9	4.9	.200	398		20.3	*3.78	6.3	21.07	99.20*	5.89		1.18	4.57	35.7	77.8		.27	0.41	0.33	Sample Lines Saturated with HC	1
128		228	4.85	21	210	7.6	.245	418		9.5	0.49	14.4	23.78	99.73	16.39		1.18	4.29	36.9	75.6		.22	0.50	0.30		1
129		71	5.26	11	317	4.0	.263	420		2.7	0.25	20.0	25.77	99.91	23.14		1.18	4.44	36.5	75.7		.31	0.48	0.46		1
132		578	2.33	324	23.1	9.4	.163	388		49.0	15.74	3.2	11.51	97.49	2.86		1.07	5.38	36.2	--		1.00	0	0.72	Blowout W_f=9.58 g/s F_m=4.44 g/kg	1
131		1133	3.96	1639	76	11.9	.207	408		54.8	45.45	6.1	20.31	94.82	5.73		1.17	4.61	36.3	79.0		.26	0.40	0.30	Pilot Flameout	1
130		87	5.52	9.3	349	3.7	.268	411		3.2	0.20	21.3	26.65	99.91	24.13		1.21	4.65	36.1	76.8		.31	0.48	0.46		3

*Inaccurate - Line Contaminated

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-2 RUN NUMBER 9 DATE 6/17/81 SHEET 3

COMBUSTOR METAL TEMPERATURES, K

ID	OUTER LINER							INNER LINER											DOME		AVERAGES			
PANEL	1	1	1	5	5	CBDY	CBDY	1	1	1	2	2	3	3	CBDY	CBDY	PILOT	PILOT	MAIN	MAIN	OUTER	INNER	TOTAL	DOME
ANGLE	0	3	6	0	6	0	6	0	3	6	0	6	0	6	3	0	SP O	SP I	SP O	SP I	LINER	LINER	LINER	
112	563	526	510	559	609	–	448	–	433	–	440	434	441	439	435	435	–	–	432	432	535	436	482	432
113	636	549	561	631	736		458		432		445	436	447	445	435	434			430	431	595	439	511	431
114	656	545	602	670	760		468		435		451	440	451	449	438	438			434	435	616	443	523	435
115	887	787	726	854	964		645		616		633	625	641	638	623	616			614	615	811	627	712	615
116	797	730	703	717	765		666		693		710	691	718	688	670	634			625	624	730	686	706	625
117	836	784	780	774	813		774		901		933	921	945	913	825	758			731	718	794	885	843	724
118	885	809	796	804	861		765		858		885	869	900	854	796	735			716	708	820	842	832	712
119	922	869	875	864	897		865		1135		1121	1081	1118	1060	936	850			844	824	882	1043	969	834
120	964	906	915	905	936		893		1220		1181	1065	1170	1015	993	862			878	870	920	1072	1002	874
121	1019	933	936	939	979		890		1186		1140	1041	1131	1000	962	856			871	862	949	1045	1001	867
124	610	523	570	623	729		454		434		447	441	453	451	436	435			433	434	585	442	508	434
123	846	790	793	781	811		778		938		935	891	936	858	878	746			735	723	800	883	845	729
122	1010	930	956	935	969		888		1171		1138	1045	1122	1001	955	858			869	871	948	1041	634	870
125	601	522	551	605	706		451		432		443	437	448	446	434	433			430	431	573	439	501	431
126	900	799	779	858	976		656		617		638	629	651	649	624	618			615	616	828	632	723	616
127	834	784	788	774	813		776		894		936	921	950	923	824	763			734	722	795	887	845	728
128	923	870	872	865	896		863		1122		1108	1081	1109	1081	941	859			843	831	881	1043	968	833

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-2 RUN NUMBER 9 DATE 6/17/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																							
	OUTER LINER							INNER LINER											DOME		AVERAGES			
PANEL	1	1	1	5	5	CBDY	CBDY	1	1	1	2	2	3	3	CBDY	CBDY	PILOT	PILOT	MAIN	MAIN	OUTER	INNER	TOTAL	DOME
ANGLE	0	3	6	0	6	0	6	0	3	6	0	6	0	6	0	6	SP O	SP I	SP O	SP I	LINER	LINER	LINER	
129	1011	928	933	933	978	-	890	-	1164	-	1153	1094	1143	1079	976	880	-	-	868	855	946	1070	1012	861
132	597	540	554	610	705		461		440		453	448	462	459	445	443			439	440	578	450	509	440
131	821	775	770	763	802		765		883		911	907	926	922	858	772			737	720	783	883	836	729
130	998	924	941	931	974		891		1153		1152	1102	1136	1116	978	886			871	855	943	1075	1014	863

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-3 RUN NUMBER 14 DATE 9/4/81 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,\,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
181	432	0.303	2.29	2.21	0.45		ERBS 12.8	18.2	18.2	298	0.120	0	8.2	15.73	1.00	4.80	462	571	0	765	1177	1.50	1.24	--
182	434	0.305	2.29	2.22	0.45			29.5	29.5	299	0.325	0	13.3	15.79	1.00	4.81	478	651	0	945	1445	1.48	0.98	--
183	430	0.302	2.29	2.25	0.45			23.8	23.8	299	0.210	0	10.5	15.94	1.02	4.81	466	604	0	855	1331	1.54	1.12	104
184	609	1.105	2.07	6.99	1.68			91.7	91.7	301	3.001	0	13.1	19.78	1.03	4.59	691	950	181.9	1158	1743	1.48	1.07	115
191	613	1.104	2.13	7.15	1.61			92.3	47.5	300	--	--	12.9	20.12	1.05	4.77	706	811	97.4	1073	1214	1.20	0.31	97
190	685	0.942	2.36	5.43	1.37			98.9	41.1	300	0.587	0.148	18.2	20.42	0.99	4.56	829	919	102.3	1264	1407	1.02	0.25	91
185	748	1.461	2.00	8.13	1.99			165.4	69.8	298	1.620	0.442	20.4	21.40	1.00	4.21	--	--	201.5	--	--	--	--	--
186	769	1.464	2.02	8.12	1.98			165.1	69.9	302	1.628	0.441	20.3	21.95	1.01	4.47	949	1065	192.1	1445	1585	1.14	0.21	98
187	806	1.680	2.02	9.11	2.19			204.3	66.7	305	1.377	0.934	22.4	22.43	1.01	4.35	1018	1168	150.4	1474	1700	1.14	0.34	89
188	804	1.683	2.01	8.97	2.17			206.4	85.3	305	2.393	0.687	23.0	22.01	0.99	4.48	1006	1129	227.8	1502	1699	1.05	0.28	91
189	806	1.682	2.00	8.98	2.19			205.4	85.3	300	2.407	0.687	22.9	22.13	1.00	4.60	1006	1124	225.4	1529	1714	1.02	0.26	95

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-2 RUN NUMBER 9 DATE 6/17/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
181		742.3	1.48	372.0	8.65	13.8	0.175	368		94.80	27.20	1.81	7.63	95.42	1.66		0.93	4.80	34.6	0		1.00	--	0.56		1
182		718.5	2.33	125.7	20.6	9.2	0.172	380		60.30	6.05	2.84	11.64	95.06	2.58		0.88	4.81	34.1	0		1.00	--	0.92	Blowout, 6.8 g/s f=3.06 g/kg	1
183		623.1	1.90	190.9	14.5	8.5	0.170	379		63.70	11.18	2.43	9.55	97.54	2.29		0.91	4.67	34.2	0		1.00	--	0.72	Rake C, Element 3 Rake D, Element 2	3
184		134.3	2.40	12.9	63.1	19.7	0.312	412		11.30	0.62	8.70	11.65	99.68	8.17		0.89	4.36	34.9	0		1.00	--	0.90		1
191		135.9	2.55	706.4	35.7	18.8	0.310	413		99.90	29.74	4.31	13.32	95.08	4.04		1.03	4.29	--	--		0.51	0.27	0.45	Main Stage Blowout	
190		132.5	3.61	9.6	89.0	5.6	0.266	406		7.41	0.31	8.17	17.59	99.80	7.63		0.97	4.63	35.3	99.2		0.42	0.46	0.53		1
185						1.9																				1
186		18.7	4.06	31.7	200.9	3.4	0.359	419		0.93	0.93	16.45	19.76	99.90	19.13		0.97	4.36	36.1	94.5		0.42	0.51	0.59		1
187		22.0	4.32	11.4	241.7	2.4	0.386	420		1.03	0.31	18.62	21.02	99.95	21.33		0.94	4.24	37.4	93.8		0.33	0.65	0.51		1
88		19.4	4.39	11.9	317.2	2.3	0.386	421		0.89	0.31	24.02	21.40	99.95	27.26		0.93	4.53	36.3	96.3		0.41	0.59	0.65	E3 Out	3
89		17.3	4.41	8.5	315.8	--	0.385	405		0.80	0.22	23.82	21.48	99.96	26.98		0.94	4.63	36.2	95.5		0.42	0.57	0.66		1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-3 RUN NUMBER 14 DATE 9/14/81 SHEET 3

COMBUSTOR METAL TEMPERATURES, K

ID	OUTER LINER								INNER LINER											DOME							
PANEL	1	1	1	5	5	CB	CB	AVG	1	1	1	2	2	3	3	CB	CB	4	AVG	PILOT	PILOT	PILOT	MAIN	MAIN	MAIN	MAIN	LINER
ANGLE	0	3	6	0	6	0	6	OUTER	0	3	6	0	6	0	6	0	6	3	INNER	SP O	SP I	DOME	SP O	SP I	DOME	DOME	AVG
181	-	509	543	571	-	454	462	508	431	430	433	434	431	438	435	436	480	437	439	610	528	454	435	-	434	492	462
182	-	529	550	651	-	454	495	535	435	435	439	435	438	449	446	441	526	540	449	785	555	456	438	-	436	534	478
183	-	509	547	604	-	446	469	515	430	430	433	430	433	441	440	434	497	442	441	738	536	450	433	-	431	518	466
184	-	789	950	871	-	685	678	795	613	613	624	611	620	648	640	618	754	651	639	793	793	640	616	-	612	691	691
191	-	755	811	740	-	677	645	726	691	674	725	-	694	738	713	665	674	684	695	599	713	629	641	-	621	641	706
190	-	840	906	833	-	760	723	812	880	790	919	-	839	911	861	783	750	812	838	674	820	705	738	-	703	728	829
185																											
186	-	937	1030	960	-	828	810	913	1053	949	1065	-	975	1049	985	873	844	924	969	881	933	793	825	-	789	844	949
187	-	974	1042	978	-	863	845	940	1164	1100	1168	-	1076	1144	1090	941	883	987	1061	914	891	824	885	-	833	869	1018
188	-	989	1078	1003	-	880	849	960	1118	1042	1129	-	1041	1110	1056	925	894	970	1032	920	956	829	870	-	828	881	1006
189	-	994	1093	1011	-	883	854	967	1107	1039	1124	-	1033	1112	1048	924	895	975	1029	831	957	831	874	-	830	865	1006

TABLE A - 14

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-4 RUN NUMBER 15 DATE 9/12/81 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
192	431	0.304	2.14	2.15	0.50	--	ERBS 12.8	30.0	30.0	293	1.23	--	13.9	15.5	0.96	5.08	498	727	20.8	958	1291	1.38	0.63	--
193	433	0.303	2.14	2.18	0.49	--		18.1	18.1	293	1.45	--	8.4	15.8	0.98	4.88	469	603	14.1	752	1126	1.62	1.17	--
194	434	0.303	2.14	2.22	0.49	--		24.1	24.1	293	0.79	--	10.8	16.0	1.00	5.33	494	706	17.2	837	1130	1.40	0.73	96
195	434	0.303	2.14	2.22	0.49	--		24.1	24.1	294	0.79	--	10.8	16.0	1.00	5.27	494	710	14.0	868	1116	1.31	0.57	104
196	460	0.381	2.14	2.76	0.66	--		28.5	28.5	295	1.14	--	10.3	17.1	1.02	5.65	525	768	16.1	856	1131	1.39	0.69	--
197	461	0.381	2.14	2.80	0.68	--		21.7	21.7	295	0.65	--	7.7	17.4	1.04	4.93	504	689	0	806	1156	1.51	1.01	--
198	461	0.381	2.14	2.78	0.67	--		35.3	35.3	296	1.76	--	12.7	17.3	1.03	5.59	535	802	17.1	963	1278	1.37	0.63	--
199	612	1.102	2.14	7.05	1.66	--		92.9	47.5	299	3.18	--	13.2	20.0	1.04	4.81	710	845	31.0	1081	1217	1.22	0.29	97
200	685	0.940	2.14	5.41	1.36	--		99.7	41.6	299	2.41	--	18.4	20.4	0.99	4.44	834	936	45.5	1242	1376	1.04	0.24	87

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-4 **RUN NUMBER** 15 **DATE** 9/10/81 **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
192		746	3.07	42.6	--	--	.193	355		48.0	1.57	3.63	15.25	98.73	3.29		.10	5.46	17.8	--		1.00	--	1.00		1
193		451	1.91	190	--	--	.200	370		46.3	11.17	2.40	9.51	97.95	2.19		.13	5.03	17.9	--		1.00	--	0.60		1
94		347	2.48	54.6	--	--	.200	369		27.9	2.52	3.20	12.16	99.12	2.96		.13	5.29	17.8	--		1.00	--	0.77	= 3.58 g/kg	1
195		326	2.47	48.7	--	--	0.207	362		26.3	2.26	3.36	12.10	99.19	3.10		1.12	5.26	17.8	--		1.00	--	0.77	Blowout W_f=7.94g/s No Sample C3, 92, B3	3
196		161	3.41	14.2	--	--	0.228	355		13.4	0.68	4.19	11.73	99.63	--		1.14	5.41	17.6	--		1.00	--	0.74		1
197		252	1.88	72.7	--	--	0.234	366		26.7	4.41	3.00	9.20	98.99	--		1.19	4.56	17.7	--		1.00	--	0.55		1
198		437	2.97	13.8	--	--	0.228	374		29.4	0.53	4.31	14.56	99.26	--		1.15	5.26	17.5	--		1.00	--	0.91		1
199		1207	2.88	554	--	--	0.310	403		80.1	21.1	4.82	14.77	96.30	4.52		1.12	4.44	17.6	--		0.51	0.28	0.48		1
200		101	3.92	12.7	--	--	0.241	398		5.2	0.37	8.43	19.12	99.85	7.85		1.04	4.52	17.6	--		0.42	0.46	0.55		1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-4 RUN NUMBER 15 DATE 9/10/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																										
	OUTER LINER								INNER LINER											DOME							
PANEL	1	1	1	5	5	CB	CB	AVG	1	1	1	2	2	3	3	CB	CB	4	AVG	PILOT	PILOT	PILOT	MAIN	MAIN	MAIN	DOME	LINER
ANGLE	0	3	6	0	6	0	6	OUTER	0	3	6	0	6	0	6	0	6	3	INNER	SP O	SP I	DOME	SP O	SP I	DOME	AVG	AVG
192	–	619	727	646	–	498	510	600	432	431	440	433	436	454	450	438	–	458	441	818	578	461	436	–	433	545	498
193	–	531	603	559	–	458	473	525	433	433	437	434	435	445	443	437	–	445	438	625	496	450	436	–	434	488	469
194	–	599	706	610	–	505	506	585	435	434	442	434	439	454	450	441	–	456	443	801	565	461	437	–	435	540	494
195	–	597	710	608	–	503	508	585	436	436	442	434	440	454	451	442	–	458	444	806	564	461	437	–	435	541	494
196	–	635	768	636	–	543	535	623	463	463	469	461	467	481	478	469	–	487	471	–	580	489	464	–	462	499	525
197	–	568	689	587	–	490	511	569	462	462	466	462	465	474	473	468	–	476	468	645	529	478	465	–	463	516	504
198	–	655	802	674	–	540	541	642	465	465	473	463	471	488	485	471	–	495	475	815	599	494	466	–	464	568	535
199	–	768	845	753	–	650	645	732	705	657	742	614	700	778	713	677	–	697	698	704	690	629	638	–	619	656	710
200	–	856	929	848	–	733	721	817	907	789	922	686	854	936	861	804	–	827	843	936	861	827	805	–	703	826	834

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-5 RUN NUMBER 16 DATE 10/6/81 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
201	433	.306	6.28	2.25	0.49	--	Jet A	23.6	23.6	299	--	--	10.5	15.9	1.00	6.10	536	749	34.5	818	1015	1.34	0.51	93
202	435	.304	5.82	2.25	0.49	--	↓	29.1	29.1	299	1.229	--	12.9	16.2	1.01	3.22	555	783	38.2	935	1154	1.30	0.44	--
203	430	.303	5.80	2.22	0.50	--		18.1	18.1	299	0.478	--	8.2	15.9	1.00	5.62	499	628	28.5	761	1032	1.44	0.82	101
204	433	.301	3.89	2.27	0.49	--	ERBS 11.8	23.4	23.4	298	0.763	--	10.3	16.4	1.03	6.28	526	714	29.6	823	1024	1.33	0.51	--
205	430	.302	3.13	2.27	0.49	--	ERBS 11.8	23.5	23.5	297	0.785	--	10.4	16.2	1.02	6.12	528	717	25.7	830	1024	1.32	0.48	--
206	431	.302	3.28	2.24	0.49	--	ERBS 11.8	23.7	23.7	296	0.808	--	10.6	16.1	1.01	5.96	533	732	24.3	840	1036	1.20	0.48	99
207	614	.665	2.12	4.19	0.96	--	↓	55.5	55.5	300	4.651	--	13.3	19.7	1.03	5.60	733	981	65.9	1159	1536	1.32	0.69	112
208	613	1.111	1.97	7.28	1.58	--		93.8	52.9	298	4.177	0.044	12.9	20.2	1.07	5.59	729	876	53.8	1069	1229	1.13	0.35	97
209	611	1.114	1.97	7.09	1.61	--		93.5	47.9	297	3.402	0.068	13.2	19.8	1.04	5.63	728	855	50.3	1083	1259	1.06	0.37	98
210	609	1.107	1.98	7.37	1.61	--		93.7	38.7	295	2.197	0.112	12.7	20.4	1.08	5.74	729	815	38.6	1066	1162	1.05	0.21	98
211	610	1.110	1.98	7.24	1.60	--		139.1	49.5	295	3.389	0.351	19.2	20.1	1.06	5.90	793	856	53.9	1275	1437	1.08	0.24	--
212	687	0.943	2.10	5.64	1.28	--		100.3	41.7	295	2.533	0.136	17.8	20.9	1.03	5.22	860	947	61.4	1275	1396	1.04	0.21	94
213	772	1.462	1.76	8.04	1.84	--		167.0	54.7	293	4.051	0.567	20.8	21.6	1.00	4.84	984	1094	78.9	1426	1602	1.15	0.27	93
214	804	1.398	1.77	7.66	1.76	--		169.5	55.8	295	4.209	0.590	22.1	22.4	1.02	5.16	1026	1141	92.2	1494	1672	1.14	0.26	94

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-5 RUN NUMBER 16 DATE 10/6/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
201		314	2.43	48.7	19.3	--	.269	362		25.6	2.27	2.59	12.01	99.21	2.58		1.14	6.07	--	--	1.06	1.00	--	0.76		
202		640	2.99	7.4	28.2	8.0	.262	367		42.1	1.03	3.05	14.92	98.93	3.04		1.16	6.05	17.2	--	--	1.00	--	0.90		
203		372	1.76	102	11.3	6.1	.269	368		41.3	6.50	2.06	8.78	98.47	2.06		1.07	5.66	17.3	--	0.97	1.00	--	0.57	Blowout @ 8.9 g/s f = 4.02 g/kg	
204		423	2.04	62.5	3.3	4.4	.269	354		41.6	3.52	3.76	9.92	98.71	3.70		0.96	5.91	17.7	--	--	1.00	--	0.70	Blowout @ 11.0 g/s f = 4.83 g/kg	
205		405	2.48	55.1	23.0	4.1	.269	350		32.8	2.56	3.05	12.07	99.00	2.97		1.16	5.85	17.5	--	--	1.00	--	0.71	Blowout @ 10.7 g/s f = 4.73 g/kg	
206		347	2.34	63.1	20.4	3.0	.279	319		29.5	3.08	2.85	11.49	99.04	2.75		1.08	5.83	17.4	--	1.00	1.00	--	0.73	Blowout @ 10.4 g/s f = 4.66 g/kg	
207		292	3.15	32.7	104	10.0	.592	352		18.6	1.19	10.90	15.41	99.46	12.20		1.16	5.32	17.0	--	0.89	1.00	--	0.92		
208		1298	2.71	2000	36.8	24.9	.745	385		86.6	76.39	4.04	14.70	91.38	3.79		1.14	5.59	17.1	0.26	0.94	0.56	0.23	0.50	Unstable Operation	
209		1374	2.62	1139	31.1	14.4	.731	386		96.8	45.97	3.60	13.91	93.76	3.33		1.05	5.25	17.1	114.9	0.96	0.51	0.27	0.47		
210		1373	2.52	733	27.9	6.2	.951	385		102.0	31.18	3.40	13.18	94.91	3.29		1.04	4.93	17.2	108.0	0.97	0.41	0.31	0.36		
211		237	4.32	224	63.5	7.6	.958	388		11.0	5.95	4.84	21.26	99.23	4.59		1.11	5.25	17.7	98.6	--	0.53	0.51	0.47	Simulated Sector Burn	
212		144	3.80	141	86.5	3.6	.814	385		7.61	4.28	7.52	18.58	99.45	7.07		1.04	4.90	17.2	104.8	1.06	0.42	0.43	0.52		
213		21	4.26	76.2	174	12.6	1.276	400		1.00	2.07	13.60	20.80	99.80	15.20		1.00	4.79	17.9	98.3	1.07	0.33	0.48	0.58		
214		34	4.60	53.3	280	4.5	1.213	389		1.47	1.34	20.30	22.45	99.85	25.10		1.02	4.93	17.9	97.6	1.06	0.33	0.51	0.61	B3 and E3 Not Sampled	

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-5 RUN NUMBER 16 DATE 10/6/81 SHEET 3

ID COMBUSTOR METAL TEMPERATURES, K

	OUTER LINER								INNER LINER										DOME								
PANEL	1	1	1	5	5	CBDY	CBDY	AVG	1	1	1	2	2	3	3	CB	CB	4	PILOT	PILOT	PILOT	MAIN	MAIN	MAIN	AVG	AVG	AVG
ANGLE	0	3	6	0	6	0	6	OUTER	0	3	6	0	6	0	6	0	6	3	SP O	SP I	DOME	SP O	SP I	DOME	DOME	INNER	LINER
201	719	633	706	585	667	–	749	676	–	434	433	438	436	445	443	447	448	452	651	641	457	436	434	434	508	442	536
202	745	665	760	628	727		783	718		437	436	443	440	451	449	453	453	458	696	635	462	439	438	436	517	447	555
203	628	585	604	547	626		572	594		431	431	435	433	440	439	439	439	442	557	504	445	433	431	431	467	437	499
204	694	605	668	575	654		714	652		434	434	439	437	445	444	445	445	450	658	623	455	436	434	434	507	441	526
205	701	620	685	578	660		717	660		433	432	437	435	444	442	444	444	450	646	615	453	434	433	432	502	440	528
206	709	630	699	583	665		732	670		433	433	438	436	445	443	445	446	452	651	612	454	434	433	433	503	441	533
207	981	839	971	845	975		812	904		612	613	618	617	630	572	632	636	643	828	717	641	618	615	613	672	619	733
208	–	787	876	743	844		774	804		701	670	707	698	717	629	668	713	674	706	670	626	631	631	619	647	686	729
209	–	778	855	730	816		774	791		703	674	714	708	733	638	674	716	681	690	664	624	628	623	617	641	693	728
210	–	745	815	711	778		775	765		719	684	738	725	757	651	688	729	691	674	656	620	626	621	615	635	709	729
211	–	768	856	738	825		791	796		854	779	856	806	850	709	738	781	745	686	670	623	650	632	624	648	791	793
212	–	863	947	826	903		885	885		885	854	885	853	881	750	816	884	801	775	771	703	722	724	703	733	845	860
213	–	924	1022	926	991		1013	975		1094	1035	1063	997	1040	853	892	1007	919	878	850	785	829	813	791	824	989	984
214	–	963	1055	980	1032		1040	1014		1141	1074	1103	1039	1095	886	938	1049	964	913	885	821	863	861	832	863	1032	1026

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-6 RUN NUMBER 17 DATE 10/13/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
215		431	.299	2.12	2.71	0.47	--		ERBS 12.8	30.9	30.9	292	0.192	--		11.4	19.0	1.24		6.16	525	732	--	911	1139	1.27	.48	109
216		430	.298	2.14	2.75	0.46	--			18.9	18.9	293	0.063	--		6.9	19.2	1.26		6.04	474	609	--	703	923	1.49	.81	--
217		429	.296	2.26	2.12	0.45	--			24.9	24.9	294	0.122	--		11.7	15.5	0.98		2.94	530	740	--	903	1123	1.30	.46	105
218		618	1.111	1.80	7.04	1.72	--			92.6	92.6	297	2.046	--		13.1	20.1	1.04		5.82	733	1012	--	1169	1564	1.65	1.03	115
219		686	.941	1.89	5.69	1.27	--			100.6	43.4	295	0.389	0.122		17.7	21.0	1.04		5.78	863	942	--	1227	1410	1.06	.34	87
220		776	2.435	1.85	13.62	3.26	--			278.8	118.8	297	2.786	1.219		20.5	22.3	1.02		5.52	996	1091	--	1415	1578	1.06	.25	92
221		805	2.803	1.84	15.07	3.48	--			335.6	110.9	296	2.317	2.417		22.3	22.0	1.00		5.42	1037	1133	--	1474	1634	1.12	.24	90
223		683	.949	1.79	5.52	1.48	--		ERBS 11.8	100.4	43.2	293	0.352	0.132		18.2	20.8	1.00		5.56	858	960	--	1222	1368	1.04	.27	85
222		805	2.797	1.80	14.90	3.53	--			335.5	111.4	296	2.279	2.363		22.5	21.9	0.99		5.35	1035	1114	--	1479	1609	1.12	.21	89
224		687	.949	1.87	5.54	1.47	--		ERBS 12.8	101.5	43.4	292	0.351	0.131		18.3	20.9	1.01		5.60	868	963	--	1239	1385	1.03	.26	86
225		802	2.802	1.87	15.35	3.54	--			335.2	110.8	294	2.286	2.337		21.8	22.4	1.02		5.64	1033	1111	--	1469	1612	1.11	.22	92
229		614	1.109	1.86	7.26	1.66	--		Jet A	93.2	93.2	291	1.981	--		12.8	20.4	1.06		6.37	726	993	--	1180	1595	1.37	.73	119
228		688	.947	1.86	5.91	1.42	--			100.8	43.2	291	.374	.145		17.1	22.0	1.08		6.49	858	920	--	1211	1362	1.05	.29	86
227		775	2.439	1.86	12.56	3.20	--			278.3	92.5	293	1.690	1.700		22.2	20.7	0.94		5.45	992	1067	--	1427	1569	1.12	.22	86
226		800	2.804	1.86	15.04	3.50	--			336.0	111.0	293	2.462	2.497		22.3	21.9	1.00		5.75	1024	1112	--	1470	1614	1.12	.22	89

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-6 RUN NUMBER 17 DATE 10/11/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
215		467	2.48	65.0	22.6	3.8	.200	369		37.1	2.98	2.96	12.24	98.86	3.29		1.07	4.04	46.4	--		1.00	--	0.85		1
216		1051	1.34	1016	--	7.1	.186	378		138	76.4	1.36	7.41	90.16	1.55		1.08	3.80	49.7	--		1.00	--	0.51		1
217		342	2.43	112	--	5.1	.179	379		28.0	5.23	3.26	11.94	98.89	3.01		1.02	3.07	47.0	--		1.00	--	0.83	Blowout W_f=11.47g/s	3
218		80	2.75	60.6	107	6.6	.345	399		5.9	2.54	12.88	13.36	99.64	11.71		1.02	5.41	42.6	--		1.00	--	0.93		1
219		177	3.75	62.2	--	3.2	.883	388		9.5	1.92	6.84	18.30	99.61	6.47		1.03	5.32	45.8	107	.9	0.43	0.43	0.55		1
220		16	4.42	295	--	8.7	2.110	414		0.8	0.77	18.88	21.54	99.92	17.46		1.05	5.25	46.9	95	.5	0.43	0.51	0.64		1
221		12	4.62	28.7	--	3.7	2.634	412		0.5	0.72	21.60	22.54	99.93	19.91		1.01	5.40	48.0	95	.2	0.33	0.62	0.52		1
223		8	3.71	18.2	--	1.4	.641	396		10.5	0.57	7.04	17.94	99.70	6.68		0.99	5.56	47.9	104	.1	0.43	0.42	0.53		1
222		21	4.65	16.6	--	--	2.096	403		0.4	0.42	22.67	22.48	99.96	20.75		1.00	5.40	48.6	96	.1	0.33	0.62	0.51		1
224		8	3.72	14.5	--	1.9	.641	388		9.3	0.46	7.57	17.87	99.74	7.08		0.98	5.53	48.3	105	.8	0.43	0.41	0.52		1
225		21	4.65	12.0	--	2.8	2.641	399		0.3	0.30	20.63	22.33	99.97	19.61		1.02	5.42	48.3	96	.7	0.33	0.61	0.50		1
229		52	2.53	9.0	--	1.5	.676	388		4.1	0.41	12.07	12.36	99.87	11.33		0.97	5.60	43.6	--		1.00	--	0.87		1
228		242	3.51	20.0	--	1.8	.614	389		13.8	0.65	5.93	17.32	99.62	5.83		1.01	5.59	46.5	99	.9	.43	0.41	0.52		1
227		7	4.36	13.9	--	1.7	1.613	365		0.3	0.37	15.26	21.47	99.96	13.17		0.97	6.12	46.9	93	.9	.33	0.60	0.50		1
226		5	4.54	13.9	--	3.5	1.827	381		0.2	0.35	18.29	22.43	99.96	17.13		1.01	5.77	46.6	93	.8	.33	0.63	0.52		1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION D-6 RUN NUMBER 17 DATE 10/13/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																										
	OUTER LINER								INNER LINER												DOME						
PANEL	1	1	1	5	5	CBDY	CBDY	AVG	1	1	1	2	2	3	3	CBDY	CBDY	4	AVG		PILOT			MAIN		AVG	AVG
ANGLE	0	3	6	0	6	0	6	OUTER	0	3	6	0	6	0	6	0	6	3	INNER							DOME	LINER
215	-	611	706	610	731	-	732	678	-	434	434	436	436	442	443	445	443	448	440	599	611	448	433	433	431	493	525
216		529	551	532	609		514	547		431	431	432	432	435	435	436	436	436	434	483	489	438	431	431	430	450	474
217		645	733	616	740		724	692		432	432	436	436	444	444	444	444	452	440	643	622	450	432	431	430	501	530
218		874	988	864	1012		831	914		622	623	626	625	638	638	634	636	653	633	798	708	639	-	619	616	676	733
219		863	922	842	900		942	894		854	823	877	844	885	853	796	879	801	846	761	782	703	-	724	697	733	863
220		968	1061	979	1063		1091	1032		1032	998	1029	964	1015	976	898	966	901	975	898	842	792	-	814	788	827	996
221		978	1050	983	1041		1083	1027		1133	1078	1109	1022	1096	1035	947	1014	953	1043	927	875	818	-	848	819	857	1037
223		867	903	844	885		960	892		862	803	876	828	873	839	812	865	794	839	768	756	702		731	696	731	858
222		980	1060	983	1046		1066	1027		1114	1042	1110	1018	1090	1034	943	1042	963	1040	911	875	820		850	821	855	1035
224		875	919	855	900		963	903		879	818	888	832	886	840	821	871	803	849	768	760	706		735	699	734	868
225		969	1060	980	1040		1056	1021		1111	1069	1104	1015	1081	1025	949	1033	966	1039	906	862	818		843	817	849	1033
229		861	951	868	993		840	903		619	619	624	623	633	631	630	634	640	628	761	704	640		618	618	668	726
228		864	920	846	894		920	889		849	805	875	835	883	841	794	871	814	841	780	771	705		730	699	737	858
227		938	1018	948	1000		1019	985		1067	1019	1061	978	1042	986	889	995	922	995	871	839	791		814	789	821	992
226		966	1054	978	1035		1036	1014		1112	1056	1103	1004	1081	1019	924	1012	955	1030	913	859	814		839	813	848	1024

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-1 RUN NUMBER 10 DATE 6/30/81 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
134	430	.300	0.84	2.19	0.54	0	Jet A	46.0	46.0	302	4.96	--	21.0	16.2	1.00	7.93	493	539	--	990	1175	1.28	0.33	--
135	430	.304	0.84	2.18	0.58	0		34.7	34.7	301	2.83	--	15.9	16.1	0.98	7.54	480	502	--	861	1032	1.24	0.40	--
133	484	.305	0.84	2.31	0.57	0		35.4	35.4	300	--	--	15.3	18.8	1.09	9.59	549	575	36.4	--	--	--	--	--
136	615	1.114	1.94	6.56	1.93	0		92.7	21.0	300	1.61	0.73	14.1	19.4	0.96	--	684	741	155.4	1036	1195	1.12	0.38	81
137	686	.946	2.14	5.43	1.23	100		98.8	22.2	300	0.87	0.02	18.2	20.0	0.99	5.92	757	789	134.1	1186	1428	1.35	0.48	78
138	770	1.467	2.14	8.12	1.82	100		164.3	38.0	302	2.22	0.06	20.2	21.6	1.01	5.56	861	892	238.0	1351	1696	1.35	0.59	84
139	804	1.688	2.14	9.33	2.12	100		199.7	46.2	304	3.24	0.11	21.4	22.6	1.03	5.47	911	954	270.0	1444	1786	1.34	0.54	88
141	801	1.691	2.03	8.90	2.02	100		199.0	46.2	308	4.64	0.09	22.3	21.4	0.98	5.16	925	963	283.0	1430	1815	1.34	0.61	84
143	682	0.944	1.86	5.77	1.27	100	ERBS 11.8	98.0	22.1	304	1.17	0.01	17.0	21.0	1.05	5.85	783	815	227.0	1124	1374	1.35	0.57	--
142	801	1.685	1.86	9.27	2.07	100		198.7	45.7	309	4.33	0.09	21.4	22.3	1.02	5.51	951	1001	374.0	1419	1785	1.31	0.59	--
144	680	.951	2.03	5.77	1.26	100	ERBS 12.8	98.8	22.4	305	1.19	0.01	17.1	20.8	1.04	5.72	780	809	225.0	1131	1416	1.37	0.63	--
146	805	1.689	1.86	8.80	2.01	100		199.9	46.0	308	4.46	0.09	22.7	21.3	0.97	5.38	955	1006	348.	1423	1800	1.32	0.61	--

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-1 RUN NUMBER 10 DATE 6/30.81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
151		431	.303	6.57	2.05	0.57	0		ERBS 12.8	37.1	37.1	300	4.20	--		18.1	15.4	0.92		7.12	509	580	30	810	1239	1.17	1.13	--
152		431	.304	6.57	2.03	0.57	0			46.8	46.8	300	4.93	--		23.0	15.3	0.91		6.16	--	--	27	1005	1309	1.22	--	--
150		619	1.109	2.26	7.11	1.48	100			92.6	21.0	302	1.06	0.02		13.0	19.9	1.05		5.80	696	725	208	971	1175	1.28	0.58	74
149		683	.944	2.03	5.57	1.25	100			95.9	22.2	303	1.21	0.01		17.2	20.4	1.02		5.62	778	806	196	1134	1433	1.37	0.66	75
148		768	1.467	1.86	7.57	1.78	100			165.5	38.6	304	3.18	0.06		21.9	20.2	0.94		5.45	900	939	281	1329	1706	1.36	0.67	--
147		801	1.691	1.86	9.06	1.98	100			199.6	46.1	308	4.56	0.09		22.0	21.6	1.00		5.60	941	986	323	1419	1796	1.34	0.61	84

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-1 RUN NUMBER 10 DATE 6/30/81 SHEET 2 Page 1

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
134		2233*	3.19	3646	8.5	4.9	.159	350		118.7*	111.0	0.74	18.52	87.58	0.69		.88	7.98	13.6	--	--	1.00	.87	--		1
135		2248*	2.44	3109	5.5	4.6	.552	354		151.3*	123.0	0.61	14.57	85.78	0.58		.92	7.88	13.6	--	--	1.00	.66	--		1
133																						1.00				-
136		349	2.55	96	51.6	2.4	.276	358		27.1	4.3	6.57	12.64	99.00	5.82		.90	--	11.0	55.2	1.22	0.23	.58	--		2
137		1210	2.89	641	65.5	6.9	.207	363		79.0	24.0	7.02	15.04	96.07	6.34		.83	6.04	15.7	414	1.23	0.23	.50	--		1
138		743	3.42	136	149	4.5	.276	349		42.5	4.5	14.04	17.20	98.62	16.01		.85	5.43	16.8	337	1.17	0.23	.56	--		1
139		631	3.64	68	--	22.9	.303	350		34.2	2.1	17.49	18.19	99.02	20.38		.85	5.14	16.9	306	1.13	0.23	.59	--		1
141		885	3.95	87	185	15.7	.296	355		43.9	2.5	15.12	19.60	98.76	16.93		.88	5.37	14.1	330	1.18	0.23	.61	--	Element B-2 Plugged	3
143		1391	2.90	765	162	27.0	.214	365		91.7	28.9	17.54	14.87	95.36	16.93		.87	5.31	13.5	521	--	0.23	.46			1
142		826	3.83	83	202	32.2	.310	357		43.3	2.5	17.36	21.40	98.75	20.26		.88	5.26	14.5	343	--	0.23	.57			1
144		1347	2.95	742	64	26.0	.193	375		87.0	27.5	6.81	15.17	95.59	6.57		.89	5.27	13.5	511	--	0.23	.46			1
146		779	4.05	59	242	26.8	.276	359		38.5	1.7	19.66	19.92	98.94	21.44		.88	5.70	14.3	335	--	0.23	.61			1

*Off Scale

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-1 **RUN NUMBER** 10 **DATE** 6/30/81 **SHEET** 2
Page 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
151		2069*	3.65	2305	20	44.1	.221	374		102.6*	65.5	1.59	19.87	91.94	1.55		1.10	8.37	11.9	--	--	1.00	.74	--		2
152		2065*	4.15	2159	22	39.7	.165	371		91.5	54.8	1.60	22.27	93.12	1.55		.97	7.37	13.9	--	--	--	.94	--	Blowout @ 6.93 g/s (f_m=3.4 g/kg)	2
150		1264	2.17	1516	32	35.2	.200	356		104.6	71.8	4.36	11.82	91.35	3.95		.91	5.27	13.4	--	1.23	.23	.35	--		2
149		1290	2.94	749	68	23.8	.186	355		83.2	27.7	7.21	15.22	95.66	6.76		.88	5.46	13.3	504	1.28	.23	.47	--		2
148		923	3.66	153	169	31.1	.214	359		49.6	4.7	14.94	18.31	98.42	16.06		.84	6.15	14.3	353	--	.23	.60	--		2
147		800	4.24	63	257	20.6	.262	360		37.4	1.7	19.80	21.06	98.97	22.36		.96	5.64	14.2	324	1.18	.23	.60	--		3

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-1 RUN NUMBER 10 DATE 6/30/81 SHEET 3 Page 1

ID	COMBUSTOR METAL TEMPERATURES, K																		
	OUTER LINER					INNER LINER									DOME				
PANEL	1	1	5	5	AVG	1	1	1	2	2	3	3	AVG	AVG	PLATE	SP	SP	CUP	
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	INNER	LINER		O	I		
134	504	467	539	568	520	–	–	–	484	484	–	455	474	500	–	–	–	430	
135	495	462	502	493	488				480	478		450	471	481				432	
133	566	528	575	568	559				544	547		514	535	549				500	
136	741	663	705	689	700				678	672		640	663	684				627	
137	775	733	789	781	770				759	736		728	741	757				688	
138	892	831	889	884	874				868	834		827	843	861				776	
139	954	876	941	932	926				922	881		874	892	911				809	
141	963	911	936	953	941				933	903		875	904	925				802	
143	815	781	793	802	798				780	768		739	762	783				689	
142	1001	948	944	960	963				971	940		896	936	951				803	
144	809	778	790	799	794				780	769		738	762	780				686	
146	1006	949	955	965	969				973	941		899	938	955				807	
151	509	502	580	514	526				500	501		458	486	509				434	
152																			

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-1 RUN NUMBER 10 DATE 6/30/81 SHEET 3 Page 2

ID	COMBUSTOR METAL TEMPERATURES, K																	
	OUTER LINER					INNER LINER									DOME			
PANEL	1	1	5	5	AVG	1	1	1	2	2	3	3	AVG	AVG	PLATE	SP	SP	CUP
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	INNER	LINER		O	I	
150	725	697	700	707	707				697	686		664	682	697				628
149	806	772	792	796	792				780	761		736	759	778				690
148	939	893	908	916	914				905	885		852	881	900				773
147	986	934	949	958	957				959	928		891	926	944				804

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-2 RUN NUMBER 12 DATE 8/17/81 SHEET 1

ID		COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
162		430	.310	4.74	2.13	0.61	0	ERBS 12.8	35.0	35.0	299	2.80	--	16.5	15.7	0.94	6.67	505	569	0	1080	1096	1.03	0.02	--
163		430	.312	5.58	2.15	0.61	0		23.8	23.8	299	1.27	--	11.1	15.6	0.94	6.71	482	514	0	792	841	1.14	0.14	--
169		431	.299	3.46	2.18	0.58	0		23.7	23.7	300	1.52	--	10.9	16.4	0.99	6.41	465	489	0	641	643	1.01	0.01	--
161		433	.311	4.00	2.22	0.61	0		29.4	29.4	298	1.96	--	13.3	16.2	0.97	6.61	499	546	0	938	973	1.07	0.07	--
160		460	.305	2.21	2.23	0.58	0		29.4	29.4	298	1.90	--	13.2	16.2	0.93	6.14	556	605	0	968	998	1.06	0.06	--
165		619	1.152	13.28	7.64	1.69	100		92.2	20.8	300	0.96	0.10	12.1	20.7	1.08	5.68	692	736	110.1	1054	1089	1.08	0.08	--
164		620	1.152	7.49	7.14	1.94	0		91.8	20.6	299	0.95	0.11	12.9	20.2	1.01	6.79	703	768	183.8	1140	1186	1.09	0.09	--
166		687	.935	3.24	5.29	1.32	100		98.7	22.3	301	1.11	0.13	18.7	20.1	0.97	5.20	793	868	164.4	1326	1384	1.10	0.10	--
167		774	1.458	7.81	8.11	1.80	100		165.0	38.4	304	3.06	0.39	20.4	21.8	1.02	4.97	915	985	328.1	1522	1614	1.13	0.12	--
168		808	1.679	5.92	9.22	2.05	100		202.4	46.3	306	4.46	0.60	22.0	22.4	1.03	4.98	970	1044	350.1	1624	1721	1.12	0.12	--

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-2 RUN NUMBER 12 DATE 8/17/81 SHEET 2

ID	MEASURED EMISSIONS							EMISSIONS CALCULATIONS						RATIOS						STOICHIOMETRY		COMMENTS	
READING	CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K	EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg	f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
162	1632	2.34	1106	14.0	15.9	.250	363	126.3	49.1	1.78	12.64	92.8	1.71	0.77	7.62	13.81	--		1.00				
163	1630	1.53	1985	6.13	30.0	.145	372	174.2	121.5	1.08	9.13	85.4	1.05	0.82	7.61	13.89	--		1.00				
169	2203	1.47	3892	5.05	30.1	.243	354	227.5	221.9	0.83	9.80	76.8	0.82	0.90	6.49	12.65	--		1.00				
161	1533	1.95	984	10.11	31.4	.266	359	141.2	51.9	1.53	10.61	92.2	1.48	0.80	6.96	13.84	--		1.00				
160	888	2.45	237	20.9	21.9	.239	354	70.2	10.7	2.71	12.39	97.4	2.62	0.94	6.21	14.05	--		1.00				
165	1166	2.23	899	29.7	23.4	.333	396	96.9	42.8	4.06	11.77	94.0	4.62	0.97	4.83	13.99	144.9		0.23				
164	329	2.60	95.3	50.1	15.2	.321	368	25.2	4.19	6.3	12.77	99.0	6.22	0.99	6.62	13.94	141.1		0.22				
166	865	3.47	215	203	18.1	.255	376	49.0	6.96	18.9	17.36	98.3	17.5	0.93	5.48	13.96	139.5		0.23				
167	482	4.01	58.9	161	19.7	.350	374	24.0	1.68	13.2	19.76	99.3	16.6	0.97	4.81	14.47	133.7		0.23				
168	451	4.71	24.4	249	10.9	.418	416	19.2	0.60	17.4	23.24	99.5	21.3	1.06	4.73	14.46	132.9		0.23				

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-2 RUN NUMBER 12 DATE 8/17/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																		
			OUTER LINER					INNER LINER							DOME				
PANEL	1	1	5	5	OUTER	1	1	1	2	2	4	4	OUTER LINER				FUEL		
ANGLE	0	6	0	6	AVG	0	3	6	0	6	0	6	AVG	AVG	SP O	SP I	CUP	DOME	
162	-	477	569	509	518	506	505	474	524	-	476	-	497	505	441	465	452	443	
163		463	514	479	485	491	481	461	502		465		480	482	443	458	453	437	
169		454	489	464	469	455	459	450	480		466		462	465	441	448	441	435	
161		475	546	498	506	505	504	474	518		475		495	499	446	489	458	443	
160		543	605	569	572	549	560	533	562		524		545	556	508	591	523	506	
165		684	736	724	715	677	684	673	700		655		678	692	643	638	648	625	
164		686	768	701	715	715	698	679	720		660		694	703	688	730	708	635	
166		779	868	843	880	770	775	758	804		744		770	793	726	718	737	701	
167		904	985	974	954	889	897	878	936		859		892	915	814	818	837	790	
168		955	1044	1031	1010	942	954	927	994		913		946	970	844	863	877	824	

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-3 **RUN NUMBER** 13 **DATE** 8/25/81 **SHEET** 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
170	425	0.298	2.87	2.37	0.50	0	ERBS 12.8	105.0	105.0	299	2.635	0	12.4	16.9	1.08	4.61	483	515	15.6	613	724	1.33	0.59	--
171	429	0.300	3.17	2.25	0.50	0		86.5	86.5	300	1.750	0	10.7	16.2	1.02	4.25	482	513	32.8	573	669	1.22	0.66	--
172	428	0.300	2.90	2.13	0.50	0		65.2	65.2	300	.991	0	8.5	15.5	0.96	3.97	472	503	67.7	503	569	1.20	0.88	--
173	614	1.111	1.91	7.22	1.59	0		319.0	63.1	302	1.139	0.085	12.3	20.1	1.06	4.67	725	759	190	934	1157	1.33	0.70	--
174	612	1.105	1.89	7.13	1.61	100		319.0	63.3	303	1.182	0.095	12.4	20.1	1.05	4.01	717	766	141	998	1191	1.16	0.50	--
175	685	0.935	1.92	5.54	1.22	100		343.0	69.7	303	1.364	0.119	17.2	20.5	1.02	3.49	819	896	234	1188	1487	1.21	0.59	--
176	773	1.458	1.93	7.76	1.81	100		580.0	124.0	305	3.678	0.368	20.8	20.9	0.97	3.62	950	1043	328	1344	1700	1.21	0.62	--
177	806	1.680	1.90	8.90	2.00	100		700.0	149.0	305	5.115	0.563	21.8	21.6	0.99	4.39	998	1095	340	1430	1825	1.23	0.63	--
178	806	1.677	1.97	9.04	2.03	100		738.0	152.0	307	5.010	0.632	22.7	22.0	1.01	4.43	1013	1144	350	1479	1850	1.15	0.55	--

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TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-3 RUN NUMBER 13 DATE 8/25/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
170		1823	1.89	2452	23.96	34.7	0.174	360		158.9	122.4	3.43	11.21	85.70	3.59		0.90	3.97	11.89	--		1.00				
171		1421	1.67	2572	7.52	36.2	0.171	362		138.9	144.1	1.21	9.97	84.30	--		0.93	4.09	11.97	--		1.00				
172		1277	1.21	2927	5.04	38.2	0.173	372		157.9	207.4	1.02	7.87	78.40	--		0.93	4.27	11.99	--		1.00				
173		478	2.16	261	100.0	15.0	0.345	390		43.3	13.5	14.90	10.77	97.80	13.82		0.88	4.17	10.83	160.2		0.20				
174		959	2.22	618	34.14	24.5	0.696	393		81.8	30.2	4.79	11.46	95.47	--		0.92	3.62	10.66	151.9		0.20				
175		1125	3.10	212	78.6	60.3	0.286	412		70.5	7.59	8.09	15.67	97.69	--		0.91	3.34	10.92	145.2		0.20				
176		664	3.64	45.8	176.3	62.3	0.368	413		36.2	1.43	15.81	18.03	99.02	--		0.87	3.84	11.87	137.6		0.21				
177		628	3.76	27.3	245.[illegible]	54.2	0.407	415		33.2	0.83	21.33	18.60	99.15	--		0.85	4.48	12.07	134.5		0.21				
178		1725	4.38	168	168.6	--	0.402	405		76.4	4.26	12.27	22.30	97.83	--		0.98	4.37	12.43	134.9		0.21			Inlet Pressure Dropped. Data Fed In From Charts	

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-3 RUN NUMBER 13 DATE 3/25/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																	
	OUTER LINER					INNER LINER									DOME			
PANEL	1	1	5	5	AVG	1	1	1	2	2	4	4	OUTER LINER		FUEL			
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	AVG	AVG	SP O	SP I	CUP	DOME
170	–	513	501	459	491	459	451	515	494	–	475	–	479	483	–	–	–	–
171	–	500	488	465	484	464	455	513	495		474		480	482				
172	–	481	466	465	471	463	453	503	479		466		473	472				
173	–	759	754	725	746	730	704	742	705		679		712	725				
174	–	735	766	702	734	710	700	736	705		678		706	717				
175	–	849	896	795	846	903	791	843	805		769		802	819				
176	–	976	1043	920	980	928	908	986	935		803		932	950				
177	–	1030	1095	963	1079	974	951	1035	983		950		979	998				
178	–	1092	1144	965	1067	970	960	1035	990		948		981	1013				

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-4 RUN NUMBER 18 DATE 10/21/81 SHEET 1

ID		COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L, max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
230		430	.297	1.83	2.17	0.53	0	ERBS 12.8	35.2	35.2	297	2.610	0	16.2	16.2	1.00	6.47	511	610	35.9	852	1080	1.25	.54	--
231		431	.301	1.83	2.19	0.54	0		29.5	29.5	296	1.809	0	13.5	16.2	0.99	6.51	504	585	32.1	791	950	1.21	.44	--
232		431	.301	1.85	2.22	0.54	0		23.8	23.8	296	1.165	0	10.7	16.3	1.01	6.30	493	557	26.2	727	834	1.17	.36	71
233		432	.298	1.83	2.26	0.54	0		17.9	17.9	296	1.026	0	7.9	16.7	1.04	6.66	477	523	17.4	636	688	1.12	.25	65
234		611	1.100	1.86	7.25	1.75	0		92.6	22.2	298	0.747	0.112	12.8	20.7	1.07	7.56	697	780	165.1	1010	1129	1.17	.30	85
235		613	1.104	1.92	7.09	1.78	100		93.4	22.1	296	0.757	0.126	13.2	20.4	1.05	5.22	702	775	193.0	1050	1211	1.22	.37	90
236		685	.937	1.82	5.38	1.59	100		99.7	23.5	296	0.872	0.149	18.5	21.0	0.99	5.33	801	900	208.0	1238	1461	1.17	.40	86
237		770	1.455	1.81	8.07	2.13	100		167.0	31.9	296	1.422	0.474	20.7	22.3	1.01	5.42	937	1020	--	1413	1661	1.15	.39	92

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-4 RUN NUMBER 18 DATE 18/21/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
230		1764	2.67	272	19.9	6.8	0.261	343		125	10.97	2.31	13.89	96.12	2.20		0.86	6.48	14.4	--	--	1.00	0.73			1
231		984	2.29	195	17.9	3.4	0.265	347		82.7	9.37	2.47	11.63	97.24	2.32		0.86	6.61	14.5	--	--	1.00	0.65			1
232		641	1.91	250	15.0	2.9	0.268	350		65.0	14.53	2.49	9.62	97.22	2.36		0.90	6.24	14.5	--	1.37	1.00	0.48			3
233		782	1.42	504	8.5	2.6	0.264	363		02.0	37.54	1.83	7.48	94.37	1.78		0.95	6.21	11.7	--	1.45	1.00	0.36		Blowout W_f=7.94g/s f=3.51 g/kg	1
234		112	2.41	24.9	24.1	5.3	0.950	394		9.4	1.19	3.32	11.68	99.68	3.22		0.91	6.58	16.9	139.0	1.17	0.24	0.58			1
235		612	2.59	270	49.1	4.9	0.978	396		46.2	11.70	6.09	12.96	97.90	5.75		0.98	4.77	16.7	132.1	1.09	0.24	0.43			1
236		515	3.41	80.3	84.5	7.0	0.823	391		30.1	2.68	8.10	16.83	99.06	7.71		0.91	5.43	16.6	130.2	1.15	0.24	0.60			1
237		307	3.90	35.1	165.6	18.5	1.273	389		15.8	1.03	14.00	19.13	99.54	16.45		0.92	5.28	17.6	129.2	1.08	0.19	0.67			1

OALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-4 RUN NUMBER 18 DATE 10/2/81 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																		
	OUTER LINER					INNER LINER								DOME					
PANEL	1	1	5	5	AVG	1	1	1	2	2	4	4	AVG			FUEL		AVG	AVG
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	INNER	SP O	SP I	CUP	DOME	DOME	LINER
230	485	496	610	588	545	-	491	484	513	490	485	469	489	513	533	435	434	479	511
231	489	494	585	563	533	-	487	484	506	488	479	468	485	494	513	435	435	469	504
232	491	484	557	535	517	-	477	479	494	481	471	464	478	471	484	435	435	456	493
233	479	468	523	508	495	-	460	470	478	468	464	454	466	456	455	434	435	445	477
234	717	689	780	746	733	-	668	672	704	668	673	651	673	828	763	627	623	710	697
235	708	694	775	744	730	-	658	679	690	728	658	686	683	636	636	621	619	628	702
236	810	795	900	861	842	-	744	768	787	826	746	775	774	719	723	693	690	706	801
237	955	941	1020	989	976	-	870	904	937	973	874	905	911	821	821	793	776	803	937

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-5 RUN NUMBER 19 DATE 11/6/81 SHEET 1

ID		COMBUSTOR AIRFLOW							FUEL FLOW							CALCULATIONS				COMBUSTOR PERFORMANCE								
READING		T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN		FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa		f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION		$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
238		431	0.303	2.11	2.46	0.42	0		ERBS 12.8	29.7	29.7	289	1.46	--		12.1	17.01	1.11		7.35	495	563	24.4	820	1029	1.48	.54	83
239		430	0.303	2.00	2.25	0.44	0			30.1	30.1	289	1.51	--		13.4	15.75	1.01		6.03	503	584	21.0	838	1101	1.58	.65	80
240		433	0.302	1.97	2.18	0.44	0			23.7	23.7	289	0.94	--		10.9	15.51	0.99		6.14	493	551	15.7	751	948	1.55	.61	75
242		459	0.378	1.88	2.63	0.50	0			28.5	28.5	289	1.35	--		10.8	15.76	0.98		5.70	525	580	26.4	795	1003	1.57	.62	80
243		431	0.303	1.97	2.21	0.42	0			23.6	23.6	289	0.93	--		10.7	15.54	1.00		6.16	493	542	--	743	916	1.55	.56	75
244		433	0.301	1.88	2.16	0.42	0			23.9	23.9	289	1.24	--		11.0	15.35	0.98		--	513	559	--	769	989	1.56	.65	79
245		434	0.303	1.96	2.21	0.42	0			18.3	18.3	288	0.69	--		8.2	15.64	1.00		5.71	495	520	--	666	829	1.51	.72	72
246		433	0.301	1.97	2.20	0.41	0			29.6	29.6	289	1.84	--		13.5	15.54	1.00		5.99	522	594	--	853	1125	1.59	.65	81
241		612	1.109	1.94	7.07	1.29	0			94.2	19.9	288	[illegible]9	0.11		13.3	19.09	1.04		5.60	710	772	87.3	1050	1299	1.52	.59	90
247		615	1.111	0.02	7.04	1.79	50			94.2	20.3	288	[illegible]5	0.12		13.4	20.18	1.03		5.43	736	783	72.3	1019	1218	1.42	.49	83
248		611	1.110	0.01	7.14	1.70	100			93.7	20.2	287	[illegible]5	0.12		13.1	20.13	1.05		4.49	730	775	67.0	995	1184	1.43	.49	80
249		689	0.943	0	7.11	1.34	100			101.2	21.6	286	[illegible]9	0.15		18.4	20.62	1.01		4.09	849	920	112.9	1188	1386	1.38	.39	78
250		776	1.462	0.04	7.96	1.82	100			169.5	27.8	286	[illegible]8	0.48		21.3	21.49	1.00		3.90	996	1074	178.9	1374	1686	1.41	.52	83
251		809	1.682	0.07	8.71	2.08	100			204.7	33.2	287	1.95	0.71		23.5	21.44	0.97		3.58	1057	1142	182.2	1471	1831	1.43	.54	85

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-5 RUN NUMBER 19 DATE 11/9/81 SHEET 2

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,\,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
253	692	0.947	0	5.48	1.55	100	ERBS 11.8	101.1	21.9	286	0.87	0.14	18.4	21.6	1.00	4.17	855	929	150.9	1178	1386	1.40	0.43	76
252	808	1.682	0.01	8.96	2.08	100		204.8	32.7	287	1.89	0.69	22.9	21.9	1.00	4.01	1059	1153	193.8	1436	1784	1.44	0.55	83
254	688	0.943	0	5.56	1.48	100	ERBS 12.8	101.2	21.9	288	0.89	0.14	18.2	21.2	1.02	4.43	842	919	135.3	1171	1367	1.40	0.41	76
255	805	1.679	0	8.97	2.15	100		205.5	34.8	288	2.04	0.69	22.9	22.0	1.00	4.23	1046	1126	183.1	1426	1686	1.38	0.42	82
261	614	1.110	1.00	7.07	1.72	100	Jet A	93.5	20.3	286	0.64	0.12	13.2	20.1	1.04	4.46	722	769	74.4	1009	1233	1.43	0.57	81
260	686	0.940	1.00	5.51	1.42	100		100.9	22.1	286	0.76	0.15	18.3	20.9	1.01	4.19	824	893	77.5	1198	1439	1.43	0.47	79
259	771	1.464	1.00	7.96	1.99	100		168.6	27.4	287	1.14	0.49	21.2	21.7	0.99	3.97	958	1033	149.8	1365	1619	1.41	0.43	82
258	809	1.681	0	8.77	2.25	100		204.5	18.8	286	0.51	0.86	23.3	21.9	0.97	4.04	1020	1094	170.8	1474	1799	1.42	0.49	85
257	805	1.682	0	8.99	2.14	100		204.1	47.6	288	3.38	0.59	22.7	22.0	1.00	3.91	1014	1086	163.2	1464	1796	1.40	0.50	86
256	805	1.681	0	8.97	2.12	100		204.8	32.9	288	1.93	0.73	22.8	22.0	1.00	3.99	1021	1106	165.2	1465	1796	1.43	0.50	86

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-5 **RUN NUMBER** 19 **DATE** 11/16/81 **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
238		964	2.07	323.6	13.4		.276	361		88.7	17.00	2.03	10.62	96.44	2.01		0.88	5.97	16.2	--	1.16	1.0	0.60		High v_{Ref}	1
239		1005	2.19	325.4	14.8		.193	343		87.6	16.26	2.12	11.21	96.53	1.96		0.84	5.90	16.2	--	1.21	1.0	0.66			1
240		--	--	--	--		.179	348		--	--	--	--	--	--		--	6.31	16.1	--	--	1.0	0.54		Rake Plugged	-
242		618	1.84	291.5	15.4		.221	349		65.0	17.56	2.67	9.27	96.96	--		0.86	5.91	16.1	--	1.21	1.0	0.54			1
243		858	1.74	455.1	1[illegible].0		.214	329		93.0	28.27	1.96	8.99	95.37	1.77		0.84	6.19	16.1	--	1.27	1.0	0.53		Blowout W_f=7.18g/s	1
244		876	2.01	367.4	15.1		.221	339		83.2	19.99	2.36	10.28	96.32	2.09		0.93	--	14.1	--	1.22	1.0	0.55			1
245		834	1.50	730.0	9.0		.221	338		102.2	51.22	1.82	7.95	93.18	1.64		0.97	5.69	14.5	--	1.29	1.0	0.41			1
246		1271	2.32	435.6	17.3		.221	336		103.6	20.33	2.32	12.00	95.81	2.09		0.89	5.98	14.4	--	1.18	1.0	0.67			1
241		120	2.54	15.3	72.4		.179	375		9.5	0.69	9.42	12.35	99.72	8.39		0.93	5.21	17.0	147.	11.11	0.21	0.66			1
247		99	2.58	15.6	65.2		.379	388		7.7	0.70	8.38	12.51	99.76	7.50		0.93	5.08	15.3	138.	91.20	0.22	0.56			1
248		464	2.65	159.2	57.9		.359	369		34.8	6.82	7.12	13.08	98.59	6.46		1.00	4.10	15.3	139.	11.23	0.22	0.45			1
249		555	3.48	41.6	97.5		.324	350		31.8	1.36	9.16	17.18	99.13	8.10		0.93	4.05	15.1	136.	11.27	0.21	0.63			1
250		336	4.02	9.3	196.9		.427	393		16.8	0.27	16.17	19.70	99.58	17.09		0.92	3.92	15.6	134.	21.20	0.16	0.72			1
251		384	4.36	6.5	257.3		.462	396		17.7	0.17	19.48	21.40	99.57	20.33		0.91	3.82	15.7	134.	21.17	0.16	0.80			1

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-5 RUN NUMBER 19 DATE 11/16/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
253		497	3.40	30.1	99.9		.324	381		29.6	1.03	9.76	16.48	99.21	8.71		0.90	4.16	15.4	139.	3 1.	31 0.2	2 0.63			1
252		302	4.34	4.0	273.6		.448	398		14.2	0.11	21.10	20.97	99.65	22.54		0.92	4.04	5.7	136.	3 1.	20 0.1	5 0.78			1
254		514	3.41	38.4	92.0		.317	381		30.3	1.30	8.92	16.64	99.17	8.16		0.91	4.29	15.3	138.	1 1.	30 0.2	2 0.62			1
255		307	4.28	5.2	250.0		.441	398		14.6	0.14	19.48	20.77	99.64	21.24		0.91	4.25	16.1	135.	1 1.	22 0.1	7 0.78			1
261		489	2.41	181.8	46.6		.372	386		39.7	8.45	6.22	12.06	98.34	5.67		0.91	4.14	16.8	136.	9 1.	23 0.2	2 0.45			1
260		483	3.22	35.4	82.1		.317	365		29.6	1.25	8.27	16.01	99.20	7.65		0.87	4.11	16.6	132.	5 1.	26 0.2	2 0.621			1
259		328	3.78	4.4	175.3		.414	393		17.3	0.13	15.17	18.70	99.58	16.85		0.88	4.02	16.9	132.	5 1.	21 0.1	5 0.72			1
258		366	4.14	4.1	225.8		.448	396		17.6	0.11	17.85	20.51	99.58	19.03		0.88	4.24	7.4	131.	9 1.	17 0.0	9 0.79		Atomization Variation	1
257		372	4.17	4.4	229.0		.448	396		17.8	0.12	17.96	20.68	99.58	19.57		0.91	4.24	17.0	134.	0 1.	15 0.2	3 0.77		Atomization Variation	1
256		360	4.23	4.6	235.7		.448	397		17.0	0.12	18.25	20.95	99.59	19.87		0.92	4.02	15.6	132.	2 1.	14 0.1	5 0.77			1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-5 RUN NUMBER 19 DATE 11/6/81 SHEET 3

ID COMBUSTOR METAL TEMPERATURES, K

	OUTER LINER					INNER LINER								DOME					
PANEL	1	1	5	5	AVG	1	1	1	2	2	4	4	AVG	FUEL				AVG	AVG
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	INNER	SPO	SPI	CUP	DOME	DOME	LINER
238	–	471	563	529	521	–	486	–	–	484	476	457	476	521	461	436	435	463	495
239	–	479	584	541	535	–	484	–	–	487	481	461	478	530	463	435	434	466	503
240	–	477	551	521	516	–	483	–	–	483	478	458	476	516	463	437	436	463	493
242	–	509	580	553	547	–	524	–	–	517	507	491	509	596	500	464	462	506	526
243	–	474	542	512	509	–	492	–	–	488	480	461	481	531	466	435	434	467	493
244	–	503	559	543	535	–	501	–	–	519	487	479	497	554	486	438	437	479	513
245	–	485	520	511	505	–	495	–	–	508	478	472	488	529	468	437	436	467	496
246	–	503	594	566	554	–	500	–	–	519	491	483	498	519	495	439	437	472	522
241	–	717	772	771	753	–	686	–	–	687	675	669	679	788	697	624	615	681	711
247	–	748	783	765	766	–	696	–	–	782	677	701	714	668	659	625	618	643	736
248	–	754	767	786	769	–	671	–	–	775	671	682	699	648	638	617	615	630	730
249	–	877	921	907	901	–	771	–	–	912	772	790	811	742	725	698	694	715	849
250	–	1035	1061	1049	1048	–	916	–	–	1074	913	927	958	850	836	845	784	829	996
251	–	1090	1129	1105	1108	–	969	–	–	1142	975	988	1019	894	883	892	817	872	1057

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-5 RUN NUMBER 19 DATE 11/6/81 SHEET 3

COMBUSTOR METAL TEMPERATURES, K

ID	OUTER LINER					INNER LINER								DOME					
PANEL	1	1	5	5	AVG	1	1	1	2	2	4	4	AVG			FUEL		AVG	AVG
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	INNER	SPO	SPI	CUP	DOME	DOME	LINER
253	–	880	929	883	897	–	809	–	–	900	793	796	825	756	740	707	702	726	856
252	–	1080	1126	1068	1091	–	1001	–	–	1153	989	994	1034	902	890	823	817	858	1059
254	–	863	919	874	885	–	787	–	–	886	781	788	810	743	731	699	696	717	842
255	–	1073	1118	1066	1086	–	981	–	–	1126	977	984	1018	896	886	816	814	853	1047
261	–	726	769	759	751	–	671	–	–	769	677	686	700	646	638	622	620	632	722
260	–	830	893	874	866	–	759	–	–	867	766	777	793	727	722	696	694	710	824
259	–	974	1034	1012	1007	–	884	–	–	1013	888	900	921	834	830	779	779	806	958
258	–	1041	1094	1077	1071	–	941	–	–	1079	948	960	982	880	873	817	816	847	1020
257	–	1041	1086	1067	1065	–	939	–	–	1068	943	953	976	884	873	814	814	846	1014
256	–	1046	1106	1076	1076	–	941	–	–	1075	948	958	980	879	876	814	813	846	1021

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V - 6 **RUN NUMBER** 20 **DATE** 11/12/81 **SHEET** 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/ AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
262	434	0.301	1.72	2.17	0.48	0	ERBS 12.8	18.3	18.3	288	0.89	--	8.4	15.77	0.99	5.94	479	508	--	666	799	1.45	0.57	70
263	432	0.300	1.79	2.16	0.48	0		23.7	23.7	288	1.55	--	11.0	15.75	0.99	6.04	488	532	--	734	905	1.50	0.56	71
264	433	0.301	1.99	2.19	0.47	0		29.2	29.2	290	2.45	--	13.3	15.79	0.99	6.02	499	557	--	803	1049	1.56	0.67	73
265	434	0.300	2.02	2.15	0.47	0		34.7	34.7	291	3.56	--	16.2	15.72	0.98	6.08	508	579	--	867	1158	1.59	0.67	70
266	432	0.301	2.05	2.52	0.54	0		27.0	27.0	291	2.08	--	10.7	18.16	1.14	8.18	486	531	--	737	916	1.50	0.59	73
268	459	0.378	2.05	2.85	0.67	0		28.2	28.2	292	2.34	--	9.9	17.69	1.06	6.84	515	551	--	758	929	1.50	0.57	77
269	432	0.301	0.86	2.20	0.54	0	ERBS 11.8	23.5	23.5	293	1.54	--	10.7	16.25	1.00	6.27	489	529	--	727	910	1.53	0.62	71
270	432	0.299	0.79	2.21	0.52	0	ERBS 12.3	23.7	23.7	293	1.57	--	10.7	16.36	1.01	6.37	489	531	--	734	919	1.55	0.62	73
271	434	0.299	0.50	2.15	0.54	0	Jet A	23.5	23.5	293	1.64	--	10.9	16.08	0.98	6.51	488	534	--	742	937	1.54	0.63	72
272	433	0.299	0.50	2.24	0.53	100		45.5	45.5	294	6.32	--	20.3	16.61	1.03	4.72	520	596	--	944	1196	1.48	0.49	--
273	433	0.301	0.50	2.20	0.54	100		40.1	40.1	294	4.93	--	18.2	16.29	1.00	4.65	514	581	--	873	1094	1.46	0.50	--
274	433	0.302	0.50	2.20	0.54	100		34.7	34.7	294	3.68	--	15.7	16.25	1.00	4.62	500	561	--	801	981	1.44	0.49	--

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-6 RUN NUMBER 20 DATE 11/12/81 SHEET 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
262		437	1.46	174.2	12.0	6.4	.234	356		58.2	13.30	2.62	7.31	97.48	2.37		0.87	6.12	12.8		1.39		0.42			1
263		511	1.79	140.2	16.0	13.2	.228	363		55.8	8.78	2.88	8.92	97.93	2.63		0.81	6.20	12.6		1.38		0.55			3
264		808	2.22	145.7	19.1	5.6	.221	371		70.8	7.31	2.75	11.15	97.70	2.51		0.84	6.10	12.3		1.34		0.66			1
265		1274	2.57	165.6	21.8	7.8	.248	371		95.0	7.08	2.68	13.13	97.15	2.43		0.81	6.32	12.1		1.39		0.80			1
266		596	1.81	103.9	14.1	2.4	.221	358		64.1	6.40	2.49	9.07	97.94	2.63		0.85	6.27	12.3		1.34		0.53			1
268		335	1.78	45.3	17.7	3.0	.248	376		37.3	2.89	3.32	8.75	98.87	--		0.88	6.04	12.1		1.28		0.49			1
269		506	1.80	127.6	15.6	4.5	.234	364		55.7	8.05	2.82	8.85	97.98	2.61		0.83	6.27	12.5		1.38		0.53			1
270		506	1.80	114.3	14.8	4.3	.221	348		55.6	7.19	2.67	8.88	98.07	2.49		0.83	6.22	12.5		1.34		0.53			1
271		468	1.81	97.4	13.9	1.3	.228	349		50.3	6.00	2.45	9.09	98.31	2.21		0.83	6.35	12.1		1.37		0.54			1
272		--	--	--	--	4.4	--	--		--	--	--	--	--	--		--	4.49	11.9		--		0.69			1
273		2449	2.79	2338	12.9	3.4	.228	369		150.7	82.40	1.31	15.96	89.32	1.20		0.88	4.65	11.9		--		0.62			1
274		2053	2.42	2615	10.9	2.6	.228	370		142.6	104.08	1.24	14.11	87.62	1.14		0.90	4.62	11.9		--		0.53			1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-6 RUN NUMBER 20 DATE 11/12/81 SHEET 3

ID COMBUSTOR METAL TEMPERATURES, K

	OUTER LINER					INNER LINER								DOME					
PANEL	1	1	5	5	AVG	1	1	1	2	2	4	4	AVG			FUEL		AVG	AVG
ANGLE	0	6	0	6	OUTER	0	3	6	0	6	0	6	INNER	SPO	SPI	CUP	DOME	DOME	LINER
262	–	474	508	492	492	–	466	–	–	481	472	462	470	459	469	439	438	452	479
263	–	479	532	508	506	–	470	–	–	487	476	467	475	463	477	444	439	456	488
264	–	483	557	527	523	–	477	–	–	494	482	474	482	466	479	469	439	463	499
265	–	487	579	540	536	–	480	–	–	499	488	479	487	468	478	517	440	476	508
266	–	471	531	502	501	–	469	–	–	483	477	466	474	470	468	438	439	454	486
268	–	503	551	529	528	–	500	–	–	514	508	497	505	494	502	476	466	434	515
269	–	478	529	504	504	–	475	–	–	490	478	470	478	473	473	458	439	461	489
270	–	477	531	506	505	–	473	–	–	488	479	470	478	477	474	461	440	463	489
271	–	474	534	507	505	–	472	–	–	485	478	469	277	476	474	469	442	466	488
272	–	489	591	596	559	–	473	–	–	487	502	501	491	454	454	439	436	446	520
273	–	488	574	581	548	–	473	–	–	490	497	494	488	452	453	437	435	444	514
274	–	488	559	561	536	–	474	–	–	489	491	437	473	451	452	437	435	444	500

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TABLE A - 23

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-7 RUN NUMBER 23 DATE 1/20/82 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %
311	434	.301	2.0	2.31	0.56	0	Jet A	29.2	29.2	287	--	--	12.6	17.10	1.05	5.82	488	528	--	--	--	--	--	--
312	434	.300	2.0	2.31	0.54	0		26.3	26.3	287	2.16	--	11.4	17.13	1.05	5.99	486	519	--	806	982	1.28	.47	83
313	435	.299	2.0	2.39	0.48	0		23.8	23.8	285	1.75	--	10.0	17.24	1.09	6.14	484	514	--	766	927	1.26	.48	85
314	434	.301	2.0	2.36	0.50	0		21.0	21.0	286	1.34	--	8.9	17.06	1.08	5.95	479	504	--	717	817	1.37	.55	81
315	435	.303	2.0	2.42	0.50	0		18.0	18.0	286	0.98	--	7.4	17.31	1.09	5.79	476	498	--	668	816	1.40	.63	78
316	433	.303	2.0	2.35	0.52	0	ERBS 11.8	23.3	23.3	287	1.60	--	9.9	16.98	1.06	5.76	483	509	--	755	923	1.30	.52	84
317	433	.303	2.0	2.39	0.52	0	ERBS 12.3	23.6	23.6	288	1.66	--	9.9	17.18	1.08	5.69	484	511	--	767	924	1.31	.47	86
318	430	.301	2.0	2.30	0.50	0	ERBS 12.8	23.3	23.3	288	1.62	--	10.2	16.56	1.04	5.78	483	510	--	756	924	1.32	.52	82
319	461	.383	2.0	2.79	0.64	0		27.6	27.6	289	2.38	--	9.9	17.04	1.03	5.94	515	541	--	792	980	1.32	.57	86
320	613	.272	2.0	1.72	0.40	0		39.1	39.1	290	5.03	--	22.8	19.67	1.03	6.67	694	758	--	1251	1468	1.15	.34	--
321	614	.558	2.0	3.50	0.89	0		41.6	41.6	290	5.76	--	11.9	19.97	1.02	6.11	680	714	--	1018	1184	1.17	.41	92
322	611	.556	2.0	3.50	0.88	50		41.5	41.5	291	5.77	--	11.9	19.91	1.02	5.48	670	703	--	1030	1184	1.21	.37	96
323	610	.550	2.0	3.51	0.88	100		41.6	41.6	291	5.78	--	11.9	20.07	1.04	5.09	659	695	--	1006	1154	1.13	.37	90

*Assumed Humidity

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-7 **RUN NUMBER** 23 **DATE** ______ **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
311		1152	3.05	214	20.5		.212	356		72.6	7.74	2.12	15.57	97.63	2.10		1.24	5.26	--		--		0.57			1
312		1004	2.99	229	18.5		.231	366		64.8	8.46	1.93	15.21	97.75	1.91		1.33	5.37	11.8		1.18		0.51			1
313		886	2.93	254	16.1		.230	373		58.4	9.60	1.75	14.90	97.80	1.74		1.49	5.13	11.8		1.15		0.45			1
313		872	2.59	270	15.8		.230	373		64.7	11.47	1.93	13.22	97.49	1.92		1.32	5.13	11.8		1.15		0.45			3
314		857	2.54	344	13.2		.232	372		64.6	14.85	1.64	12.98	97.20	1.62		1.46	5.14	11.9		1.20		0.40			1
315		938	2.13	598	10.4		.233	373		82.4	30.07	1.50	11.14	95.46	1.49		1.51	4.86	12.0		1.22		0.33		Blowout W_f=9.4g/s f=3.91 g/kg	1
316		995	2.90	303	19.0		.232	346		67.5	11.79	2.12	14.43	97.38	2.08		1.46	5.11	12.2		1.16		0.45		Blowout W_f=10.2g/s f=4.34 g/kg	1
317		972	2.93	272	18.6		.245	355		65.1	10.43	2.04	14.65	97.56	2.03		1.48	4.87	12.1		1.13		0.45		Blowout W_f=10.0g/s f=4.16 g/kg	1
318		962	2.91	259	19.5		.231	350		64.2	9.88	2.14	14.69	97.64	2.08		1.44	5.34	12.1		1.19		0.46		Blowout W_f=10.2g/s f=4.45 g/kg	1
319		584	2.85	94.3	25.2		.256	359		40.5	3.75	2.88	14.13	98.72	2.88		1.43	5.64	11.8		1.15		0.45			1
320		2477	4.58	25.4	61.1		.217	372		103.9	0.61	4.21	23.60	97.50	6.75		1.04	6.33	11.5		--		1.03			1
321		269	3.32	6.0	58.8		.315	396		16.3	0.21	5.84	16.24	99.60	7.10		1.36	5.84	11.4		1.08		0.54			1
322		247	3.33	13.5	52.1		.316	399		14.9	0.47	5.16	16.28	99.61	6.35		1.36	5.23	11.4		1.04		0.46			1
323		731	2.94	256	37.5		.319	389		48.7	9.75	4.10	14.73	98.01	5.14		1.24	4.75	11.4		1.09		0.38			1

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ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-7 RUN NUMBER 23 DATE 1/20/81 SHEET 3

COMBUSTOR METAL TEMPERATURES, K

ID	OUTER LINER					INNER LINER								DOME				AVG
PANEL ANGLE	10	16	50	56	OUTER AVG	10	13	16	20	26	40	46	INNER AVG	S/P OUTER	S/P INNER	CUP DOME	DOME AVG	LINER
311	475	469	528	524	499		463		485			475	474	469	479	440	463	488
312	476	468	519	518	495		464		485			473	474	466	479	439	461	486
313	477	468	514	513	493		465		482			471	473	464	476	438	459	484
314	474	463	502	504	486		463		480			468	470	460	471	437	456	479
315	469	459	494	498	480		463		483			464	470	457	467	438	454	476
316	478	467	505	509	490		469		479			473	474	465	476	437	459	483
317	477	468	511	510	492		468		478			474	473	466	475	440	460	484
318	475	466	509	510	490		466		481			471	473	465	474	439	459	483
319	510	499	539	541	522		499		515			500	505	493	506	470	490	515
320	679	658	758	748	111		663		690			663	672	731	781	622	711	694
321	672	660	712	714	690		669		682			654	668	661	708	622	664	680
322	664	657	703	686	678		671		666			645	661	643	634	617	631	670
323	644	652	695	688	670		646		658			635	646	633	629	615	626	659

TABLE A - 24

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-8 RUN NUMBER 24 DATE 4/22/82 SHEET 1

ID	COMBUSTOR AIRFLOW						FUEL FLOW						CALCULATIONS			COMBUSTOR PERFORMANCE								
READING	T_3 - TEMPERATURE, K	P_3 - PRESSURE, MPa	h - HUMIDITY	W_c - COMBUSTOR AIRFLOW, kg/s	W_b - BLEED AIRFLOW, kg/s	G - VARIABLE GEOMETRY POSITION, % OPEN	FUEL TYPE	W_{ft} - TOTAL FUEL FLOW, g/s	W_{fp} - PRIMARY FUEL FLOW, g/s	T_f - FUEL TEMPERATURE, K	ΔP_{fp} - PRIMARY FUEL PRESSURE DROP, MPa	ΔP_m - MAIN FUEL PRESSURE DROP, MPa	f_m - METERED FUEL/AIR RATIO, g/kg	V_r - REFERENCE VELOCITY, m/s	FF - REFERENCE FLOW FUNCTION	$\Delta P/P$ - PRESSURE DROP, %	T_L - AVERAGE LINER TEMPERATURE, K	$T_{L,max}$ - PEAK LINER TEMPERATURE, K	Q_r - RADIANT HEAT FLUX, kW/m^2	T_{39} - AVERAGE EXIT TEMPERATURE, K	$T_{39,max}$ - PEAK EXIT TEMPERATURE, K	PROFILE FACTOR	PATTERN FACTOR	η_{tc} - T/C COMBUSTION EFFICIENCY, %*
324	615	1.107	0.93	7.78	1.10	100	ERBS 12.8	93.2	0	287	0	0.26	12.0	20.47	1.15	4.81	700	756	--	1130	1231	1.11	.20	117
325	685	.941	0.93	6.06	0.93	100		102.4	0	286	0	0.30	16.9	21.11	1.11	4.63	788	888	--	1415	1437	1.02	.03	123
326	771	2.436	0.50	14.27	2.01	100		281.9	0	288	0	1.80	19.8	21.38	1.07	4.30	903	982	--	1463	1588	1.03	.18	103
327	802	2.586	0.50	14.24	2.15	100		347.3	0	289	0	2.74	24.4	21.08	1.03	4.58	947	1054	--	1570	1694	1.03	.16	--
328	800	2.793	0.50	15.88	2.33	100		348.1	0	289	0	2.80	21.9	21.62	1.06	4.26	942	1045	--	1586	1741	1.12	.20	108
329	760	2.794	0.50	15.88	2.53	100		348.2	0	289	0	2.81	21.9	20.74	1.03	4.34	895	990	--	1543	1690	1.09	.19	107
330	805	2.789	0.50	16.15	2.51	100		347.8	0	290	0	2.76	21.5	22.34	1.08	4.84	951	1053	--	1556	1704	1.10	.20	104
331	808	2.796	0.50	15.72	2.76	100		307.8	0	290	0	2.16	19.6	22.12	1.05	4.39	945	1033	--	1503	1631	1.09	.19	--
333	685	.932	0.50	5.77	0.77	100	ERBS 11.8	100.2	0	290	0	0.27	17.1	19.96	1.06	4.53	801	878	--	1305	1412	1.14	.17	103
332	756	2.792	0.50	15.67	2.88	100		348.5	0	290	0	2.74	22.2	22.19	1.05	4.71	953	1058	--	1586	1738	1.06	.17	105
334	687	.943	0.50	5.72	0.83	100	ERBS 12.3	101.3	0	291	0	0.28	17.7	19.80	1.04	4.51	797	878	--	1299	1386	1.13	.14	99
335	760	2.782	0.50	15.27	2.92	100		349.3	0	291	0	2.73	22.9	21.92	1.03	4.88	952	1043	--	1537	1666	1.13	.18	96
338	618	1.107	0.50	7.69	1.10	100	Jet A	95.0	0	291	0	0.25	12.4	20.34	1.14	5.28	686	756	--	1106	1174	1.10	.14	106
337	684	.943	0.50	6.01	0.73	100		102.8	0	290	0	0.30	17.1	20.28	1.10	4.53	776	880	--	1321	1409	1.09	.14	105
336	756	2.799	0.50	15.24	2.90	100		345.7	0	290	0	2.86	22.7	21.62	1.02	4.58	944	1048	--	1559	1674	1.08	.15	99

* Based on 4 T/C's (elements 2 & 3 of rakes A & F)

TABLE

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-8 **RUN NUMBER** 24 **DATE** 1/22/82 **SHEET** 2

ID		MEASURED EMISSIONS								EMISSIONS CALCULATIONS							RATIOS						STOICHIOMETRY		COMMENTS	
READING		CO - CARBON MONOXIDE, ppm	CO_2 - CARBON DIOXIDE, %	HC - UNBURNED HYDROCARBONS, ppm	NO_x - OXIDES OF NITROGEN, ppm	SN - ESTIMATED SMOKE NUMBER	P_s - SAMPLE LINE PRESSURE, MPa	T_s - SAMPLE LINE TEMPERATURE, K		EICO - CO EMISSION INDEX, g/kg	EIHC - HC EMISSION INDEX, g/kg	$EINO_x$ - NO_x EMISSION INDEX, g/kg	f_s - SAMPLE FUEL/AIR RATIO, g/kg	η_s - SAMPLE COMBUSTION EFFICIENCY, %	$EINO_{x,c}$ - ENGINE $EINO_x$, g/kg		f_s/f_m	$\Delta P/P/FF^2$	$W_{fp}/\Delta P_{fp}^{1/2}$	$W_{fm}/\Delta P_{fm}^{1/2}$	η_s/η_{tc}	W_{fp}/W_{ft}	ϕ_m - MAIN STAGE PRIMARY EQUIVALENCE RATIO	ϕ_p - PILOT STAGE PRIMARY EQUIVALENCE RATIO		EMISSIONS SAMPLING MODE
324		531	2.92	210	55.6	9	.552	399		35.9	8.15	6.18	14.48	98.45	5.70		1.21	4.39		121	5 0	84	0.39			1
325		584	3.83	78.6	98.4	16	.462	392		30.3	2.34	8.39	18.95	99.08	7.88		1.12	4.66		122	7 0	81	0.54			1
326		192	4.50	6.9	263	33	1.062	411		8.6	0.18	19.34	22.03	99.78	17.21		1.11	4.61		138	4 0	97	0.64			1
327		248	5.15	6.0	355	41	1.117	414		9.7	0.13	22.83	25.31	99.76	20.54		1.04	5.40		138	2	--	0.79			1
328		185	4.81	6.1	344	39	1.151	416		7.8	0.15	23.69	23.55	99.80	21.47		1.08	4.69		137	1 0	92	0.71			1
329		--	--	--	--	--	1.179	415		--	--	--	--	--	--		--	4.98		136	9	--	0.71			1
330		170	4.73	4.0	352	--	1.186	421		7.3	0.10	24.67	23.13	99.82	22.51		1.08	5.08		138	0 0	96	0.69			1
331		122	4.16	3.1	317	--	1.213	423		5.9	0.09	25.24	20.31	99.85	22.44		1.04	4.89		138	2	--	0.63			1
333		563	3.32	71.9	88.2	22	.455	401		34.2	2.50	8.79	16.17	98.97	7.77		0.95	4.87		127	7 0	96	0.55			1
332		178	4.74	4.5	358	--	1.172	420		7.7	0.11	25.36	22.86	99.81	22.79		1.03	5.26		138	8 0	95	0.72			1
334		529	3.43	61.7	89.5	22	.455	400		31.0	2.07	8.60	16.79	99.09	7.44		.95	5.09		127	2 1	00	0.57			1
335		136	4.38	4.0	321	--	1.241	421		6.3	0.11	24.49	21.20	99.84	21.42		.93	5.55		139	3 1	04	0.74			1
338		567	2.43	231	39.9	6.6	.579	407		45.4	10.62	5.25	12.22	98.02	4.71		.99	--		124	3 0	92	0.40			1
337		504	3.37	54.7	83.6	8.4	.461	406		29.6	1.84	8.06	16.75	99.15	7.24		.98	4.58		123	8 0	94	0.55			1
336		137	4.34	2.7	296	28	1.213	420		6.3	0.07	22.42	21.42	99.85	19.68		.99	5.33		134	8 1	01	0.73			1

ALTERNATE FUELS COMBUSTOR TECHNOLOGY PROGRAM

TEST DATA SUMMARY

COMBUSTOR CONFIGURATION V-8 RUN NUMBER 24 DATE 1/22/82 SHEET 3

ID	COMBUSTOR METAL TEMPERATURES, K																	
	OUTER LINER					INNER LINER								DOME				
PANEL	1	1	5	5	OUTER	1	1	1	2	2	4	4	INNER	S/P	S/P	CUP DOME	DOME	AVG
ANGLE	0	6	0	6	AVG	0	3	6	0	6	0	6	AVG	OUTER	INNER		AVG	LINER
324	694	683	756	–	711	–	680	–	688	700	–	–	689	649	651	622	640	700
325	791	755	888		811		745		771	778			765	726	719	691	712	788
326	884	859	982		908		868		900	926			898	822	808	778	802	903
327	925	893	1054		957		905		938	972			938	855	841	809	835	947
328	921	891	1045		952		901		932	964			932	847	836	807	830	942
329	864	849	990		901		859		891	912			887	808	799	768	792	895
330	925	897	1053		958		915		944	972			944	851	845	809	835	951
331	927	899	1033		953		910		938	964			937	854	845	814	838	945
333	799	766	878		814		773		792	795			787	738	723	700	720	801
332	937	898	1058		964		914		949	960			941	856	847	813	839	953
334	790	761	878		810		770		792	791			784	736	724	699	720	797
335	926	895	1043		955		923		960	967			950	859	851	815	842	952
338	681	659	756		699		666		678	678			674	641	643	624	636	686
337	761	733	880		791		749		762	768			760	722	719	696	712	776
336	911	885	1048		948		911		948	960			940	855	843	814	837	944